OPERATIONAL PERFORMANCE ASSESSMENT

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EXECUTIVE SUMMARY

This report provides an overview of recent FAA Next Generation Air Transportation System (NextGen) improvements and the corresponding operational impacts observed in the National Airspace System (NAS). The FAA's objectives are to determine if the desired impacts were achieved, quantify these impacts, and identify any unanticipated effects.

The FAA's NextGen office focused on a select set of NextGen improvements implemented by fiscal year 2015. They are Houston Metroplex, wake recategorization, enhanced low-visibility operations and improved data sharing. We included the implementations for which sufficient time has passed to conduct a meaningful analysis. Our aim was to estimate the impacts of NextGen capabilities on airspace operations in a systematic and standardized way.

HOUSTON METROPLEX

The FAA implemented multiple changes to the first key metroplex location in Houston on May 29, 2014. Houston metroplex includes two major and 16 satellite airports, a complex airspace consisting of segments controlled by two center air traffic control (ATC) facilities and a major terminal ATC facility, and several Class D airspace units. Houston Metroplex improvements incorporated minor airspace adjustments and numerous changes to the procedures for Houston Intercontinental (IAH) and Houston Hobby (HOU) airports, including publication of 49 new Performance Based Navigation procedures, modification of 11 existing procedures, and elimination of 20 procedures. In addition, traffic to IAH and HOU is now supported by Time Based Flow Management automation, which continues to be adjusted in response to the new routing structure and still developing operating practices.

In early 2015, MITRE Corp. completed a post-implementation review of Houston Metroplex improvements and estimated an annual benefit of $6.1 million to the operators at the two largest airports in the area. Our analysis complements MITRE's study by highlighting continuous descent operations and encompassing impacts observed over a longer study period. We focused on operational and performance impacts, and did not attempt to monetize the corresponding savings.

Since the implementation of Houston Metroplex improvements, both IAH and HOU can accommodate more operations during peak hours despite a decrease in facility reported airport departure and arrival rates. Also, IAH now accommodates about 10 more and HOU three more operations per hour during instrument meteorological conditions. However, improved airport efficiency has not yet led to improvements in flight efficiency on the airport surface.

Trade-offs in airborne flight efficiency were prominent for both arrivals and departures. Although arrivals now fly up to 1.6 percent longer distances within 300 nautical miles (nm) of the two airports, their cruise is longer and descent more efficient. Longer cruise and shorter descent phases of flight mean longer time and distance spent at higher, more fuel-efficient altitudes, and consequently more efficient flight profiles. Departures fly up to 1.1 percent longer distances within 300 nm of the two airports and experience a 4.0-5.5 percent longer cruise as well. However, cruise altitude is about 700 feet lower on average.

Because one of the key goals of Houston Metroplex improvements was to facilitate continuous descents into IAH and HOU, we investigated changes in descent profiles more carefully. Arrivals are over three times more likely to execute continuous descents – the rate of continuous descent operations increased from 13 to 41 percent of all arrivals to the airports – with their top of descent (TOD), the point at which an aircraft transitions from the cruise to the descent phase of flight, about 13 nm and two minutes closer to the two airports. Impacts on flights with step descents were mixed, with their TOD about 4 nm farther away from the two airports and time in level flight below TOD three minutes longer on average. However, flights with step descents now level off at over 3,000 feet higher altitude on average.

Arrivals from San Antonio are the biggest beneficiaries of improvements introduced through the Houston Metroplex project, with average distance and time savings of 3 nm and 41 seconds, nearly a fourfold increase in the proportion of flights executing continuous descents, and more than 1,000 foot increase in altitude of level segments.

Area Navigation (RNAV) Standard Terminal Arrival use is high across the board, with more than 55 percent of arrivals to the two airports conforming to more than 80 percent of the filed procedure portions. Use of RNAV standard instrument departures is lower because of a heavy use of direct-to clearances: about 30 percent of departures from IAH and 15 percent of departures from HOU conform to more than 80 percent of the procedure after the joining waypoint.

WAKE RECATEGORIZATION

Air traffic controllers in the United States currently use two classifications and sets of separation standards to avoid wake turbulence from nearby aircraft during approach and takeoff: traditional and recategorized wake classes (RECAT). While the traditional wake separation classes are based on maximum takeoff weight, the new RECAT categories also consider aircraft wingspan and approach speed, providing for a more accurate characterization the risk of wake encounters. As a result, separations for many combinations of aircraft categories can be safely reduced with RECAT, especially for those behind the traditional Heavy class and the Boeing 757 aircraft. At the first four facilities authorized to use RECAT, departure throughput increased almost immediately after implementation. An increase in arrival throughput took longer to achieve, and in some cases required additional adjustments such as location and capacity of corner posts through which aircraft transition from enroute centers to Terminal Radar Approach Control facilities.

Air traffic controllers took about three to four months to get comfortable with the new aircraft categorization and separations at the first four facilities authorized to use RECAT. At that point, they started declaring higher airport arrival and departures rates. Although the maximum rates generally increased, they were used infrequently. However, the high-end range of airport departure rates and airport arrival rates was used more frequently after RECAT, indicating that the controllers can now sustain a high-pressure workload for longer periods of time.

At Memphis (MEM), Louisville (SDF) and Cincinnati (CVG) airports, the average peak quarter-hour throughput increased by at least one departure and up to one arrival per runway. The highest increase in peak throughput was observed at MEM, equivalent to 13 additional operations per hour. In addition to the high proportion of aircraft that are directly affected by the new separations (previously classified as Heavy and now as Category C), this outcome was also partially caused by a significant growth of the Boeing 757 fleet at MEM. On the other hand, throughput improvement in ATL was hidden by reduced demand and the preponderance of aircraft less affected by RECAT. However, throughput of ATL's dominant Runway 27R increased by about two arrivals and two departures per hour, an improvement mostly driven by traffic spilling over from the crossing Runway 28. More importantly, the reduced reliance on the remote Runway 28 also resulted in shorter taxi-out times.

Departure queue delays decreased at the three locations with Airport Surface Detection Equipment-Model X (ASDE-X) surveillance: around three minutes at MEM and just under a minute at SDF and ATL. Average taxi-out times decreased as well, resulting in overall taxi-out time savings between 1.2 and 4.6 minutes.

At the three locations where we were able to study changes in taxi-out times, we observed decreased average values after deployment of RECAT separations. Since RECAT deployment and through the end of FY 2014, these savings accumulated to over 86,000 minutes at ATL, while the overall savings during peak periods accumulated to about 148,000 minutes at MEM and 22,000 minutes at SDF.

For nearly all arrival fix-runway pairs, average time in terminal airspace decreased after deployment of RECAT separations. Since RECAT deployment and through the end of FY 2014, these savings accumulated to almost 93,000 minutes in ATL, while the overall savings during peak periods accumulated to about 12,000 minutes at MEM, 8,900 minutes at SDF and 1,200 minutes at CVG.

ENHANCED LOW-VISIBILITY OPERATIONS

During the last few decades, numerous airports across the NAS improved their runway guidance and lighting systems. Operators also invested in many cockpit technologies that enhance pilot awareness of their surroundings near and on the surface. For example, Head-Up Displays (HUDs) provide flight and navigation information on a clear panel that pilots can review while looking out the window. With this more integrated view in a single field of vision, pilots now can execute safe precision approaches during some of the low-visibility conditions that used to halt landings. Runway visual range (RVR) and decision height minima for approaches are now as low as 1,000 feet and 100 feet for Category II, and 1,400 feet and 150 feet for Category I approaches.

After reduction of RVR minima requirements, airport access during low-visibility conditions improved in two ways: periods of time with no access occur almost 6 percent less frequently and 17 percent more flights were able to land during such conditions.

Although these benefits were spread mostly across airports supporting Special Authorization (SA) CAT I operations, our study confirmed that facilitating SA CAT II operations results in a more significant benefit by enabling airport access during periods when none was previously available.

INFORMATION SHARING

NAS users rely on many types of information provided by the FAA. Some of that information is static and made available via products with regular publication cycles, such as aeronautical charts. However, we also are sharing more real-time data, such as surveillance, traffic flow management, weather observations and forecasts, and other dynamic updates, such as the status of special use airspace. The FAA traditionally shared such information using a variety of technologies, including radio, telephone, Internet, and dedicated connections. However, in recent years, we leveraged new information management technologies to improve information delivery and content.

Improved delivery typically results in lower costs while improved content should enable operational benefits. Operational impacts of these improvements will depend on the particular information needs of users. Improved outcomes arrive only when better information content and delivery are used to influence decisions. To determine how this information is being used, and what, if any, the benefits of using it may be, we interviewed data consumers.

Airlines and airports report using FAA data to improve their operations, with the most extensive use supporting enhanced awareness of operating conditions and flight status, especially on the airport surface and in situations when aircraft transition from the control of one entity to another. Improved awareness typically enables more proactive engagement with flight re-planning, including the ability to anticipate dynamically evolving conditions and events affecting individual flights as well as overall flows of traffic. All of this means improved resource management by the data consumers, especially when supported by automated decision support tools and ex post analytical capability.

Airlines and airports also report increased benefits when integrating multiple complimentary data sources. For example, ASDE-X surface surveillance data can be displayed alone, but it also can be combined with actual and scheduled time information to yield useful decision-support applications. On the other hand, users said that aeronautical information about airspace restrictions will be more useful once it is fully digitized and combined with planned flight trajectories in various decision support tools.

While users reported using data from the System Wide Information Management Terminal Data Distribution System and Traffic Flow Management System the most, they also were interested in additional data products once they become more mature. Our research confirms that obtaining the live subscriptions is only the first step; this needs to be followed by developing parsers, displays and automation before the data becomes truly useful. External users now consume just a subset of the data that has been made available. Some of the data elements are new and require time for users to understand their potential for practical use. Also, the cost of developing tools that transform this data into valuable information remains the key impediment to more extensive use.

Because the FAA shares the data free of charge, there has always been a question about its actual value. End users either invest their own time and money to connect to and parse the data or pay a third-party vendor for the service. This is only a partial picture of the value proposition, and in any case, the amount spent on these transactions was unavailable to inform our study.

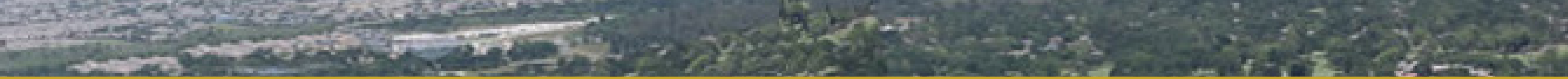
INTRODUCTION

This report provides an overview of recent FAA Next Generation Air Transportation System (NextGen) improvements and the corresponding operational impacts that were observed in the National Airspace System (NAS). The FAA's objectives are to determine if the desired impacts have been achieved, to quantify these impacts, and to identify any unanticipated effects.

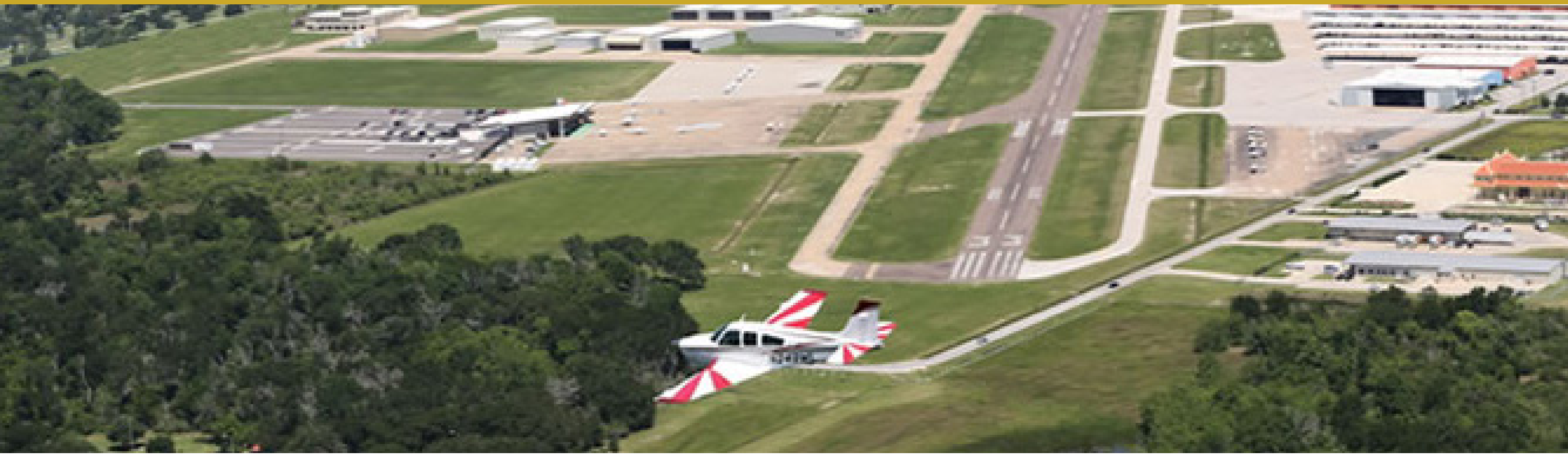
The NextGen office focused on a select set of NextGen improvements that were implemented by fiscal year 2015. They are Houston Metroplex, wake recategorization, enhanced low-visibility operations and improved data sharing. We included the implementations for which sufficient time has passed to conduct a meaningful analysis. Our aim was to estimate the impacts of NextGen capabilities on airspace operations in a systematic and standardized way.

One of the most challenging problems with performance analysis is determining if an operational improvement is directly responsible for observed changes in performance. The NAS is a highly dynamic and adaptable system with major actors, including pilots, air traffic controllers, airline operation centers and airline dispatchers, continually evaluating and adjusting to the current conditions and restrictions. More importantly, air traffic controllers are quite creative and efficient, and often manage to safely accommodate additional operations by taking advantage of even the smallest gaps in flows.

Although such high-end performance of the actors definitely improves system and operator efficiency, it also complicates performance and benefit analyses by disguising the fact that such performance was much more difficult to achieve in the past. In addition, subtle changes in demand also can disguise improved performance. For instance, a decrease in demand can contribute to shorter taxi times as much as an improvement aiming to increase efficiency of surface operations. Therefore, when analyzing performance, we report overall performance impacts together with changes to individual factors, and if feasible, contribution of individual factors to overall changes in performance.



POST-IMPLEMENTATION ASSESSMENT OF HOUSTON METROPLEX IMPROVEMENTS



The FAA's Metroplex program investigates operational challenges in metropolitan areas with complex air traffic flows and proposes integrated solutions that deliver more efficient operations without compromising safety. Metroplex is a system of airports that operate in close proximity of each other and serve one or more major nearby cities. A metroplex includes at least one major commercial airport and often numerous smaller airports typically serving the general aviation (GA) community.

Guided by a tightly governed process, Metroplex studies are a collaborative undertaking between community representatives and industry stakeholders, including air traffic controllers, airport officials, and commercial and GA operators[1]. The representatives and stakeholders form the Study Teams to identify operational challenges specific to each Metroplex, and design and implement comprehensive and integrated solutions resulting in optimized airspace use and improved regional traffic flows. As part of the FAA's NextGen initiative to transition to a full Performance Based Navigation (PBN) system by 2030, the Metroplex Program capitalizes on satellite-based technology and concepts, and develops region-specific solutions that focus on all of the airports and users at the same time rather than their

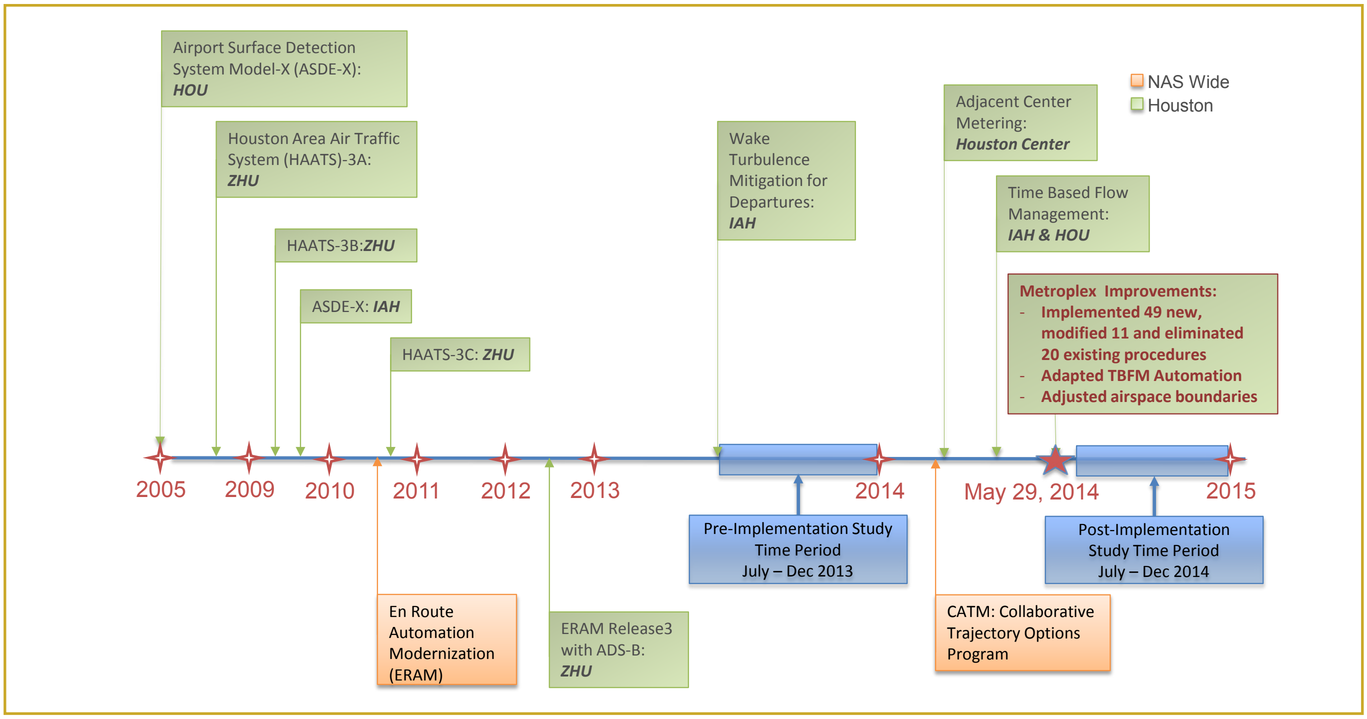


Figure 1 - Timeline Capturing Improvements in the Houston Metroplex Area

[1] For more information, please visit https://www.faa.gov/air_traffic/flight_info/aeronav/procedures/oapm/ and http://www.metroplexenvironmental.com/oapm.html

individual challenges and needs. The solutions include publishing new PBN procedures, realigning existing PBN and conventional routes, adjusting airspace boundaries, and enhancing automation to support integrated terminal and surface operations.

Operational benefits are a core of each Metroplex study, including reduced complexity of air traffic flow interactions and air traffic control (ATC) tasks, further resulting in less workload and decreased need for pilot/controller communications and traffic management initiatives. In addition, increased reliance on PBN technology and routing options also delivers more predictable and repeatable flight trajectories, and often more efficient lateral and vertical flight profiles, including reduced fuel consumption.

Over the last 10 years, many of the improvements in the Houston Metroplex area allowed for an adjustment period after each implementation (Figure 1). However, in 2014 Collaborative Air Traffic Management, Adjacent Center Metering and Time Based Flow Management led up to the Metroplex improvements. Insufficient time between these and Metroplex improvements made it impossible to determine impacts each of them may have individually contributed to the overall performance impacts.

The FAA implemented multiple changes to the Houston Metroplex on May 29, 2014. It was the first key site that included George Bush Intercontinental Airport (IAH), William P. Hobby Airport (HOU), 16 satellite airports within the region, and airspace controlled by the Houston Terminal Radar Approach Control (I90 or Houston TRACON) and Houston Air Route Traffic Control Center (ZHU or Houston Center). Focused on operations at the two busiest airports, Houston Metroplex improvements incorporated minor airspace adjustments, 49 new PBN procedures, modification of 11 existing procedures and elimination of 20 procedures. In addition, IAH and HOU traffic is now supported by the TBFM program, which was fully adapted to take advantage of the new airspace and routing structure.

Although the Houston Metroplex Study Team developed solutions that focused on operations at IAH and HOU, it considered challenges and restrictions applicable to the 16 satellite airports and overall airspace supporting the Metroplex. Describing the problem as complicated and solution as complex is an understatement. The study team scrutinized more than 80 procedures before agreeing on a regional solution within an area that includes segments of two ATC centers as well as a major TRACON facility and several Class D airspace units. While 12 of the 60 procedures aimed to facilitate more efficient continuous descents into IAH and HOU, limited airspace is available for such complex interactions.

In early 2015, MITRE Corp. completed a post-implementation review of Houston Metroplex improvements and estimated an annual benefit of $6.1 million to the operators at the two largest airports in the area. This analysis by the FAA's NextGen Office complements MITRE's study by addressing additional impacts on aircraft ability to execute continuous descents and investigates impacts observed over a longer study period. We focused on operational and performance impacts, and did not attempt to monetize the corresponding savings.

HOUSTON METROPLEX CHALLENGES AND PROPOSED SOLUTIONS

The Houston Metroplex Study Team identified many challenges limiting efficiency of operations in this region, including unused enroute transitions, lack of runway transitions and numerous altitude restrictions used to deconflict major traffic flows. Use of existing procedures was low, including dual-use[2] procedures, and excessive vectoring frequently was necessary to provide for safe flow merging and sequencing. Standard Terminal Arrival Routes (STARs) and Standard Instrument Departures (SIDs) did not facilitate continuous descents and climbs. The shape and size of the frequently congested airspace in the northwest introduced additional challenges with effective metering and procedure use. Traffic in and out of Ellington Field Class D airspace in the southeast introduced flow merging challenges resulting in reduced operational flexibility and increased controller workload, as did limited headings available for southwest-bound departures from IAH's runways 15L and 15R.

Proposed changes to arrival procedures focused on implementation of Area Navigation (RNAV) STARs with Optimized Profile Descents (OPDs) for arrivals to IAH and HOU. Designed to reduce interaction between air traffic flows across the TRACON, OPDs reduce workload for controllers and pilots. They aid controllers by reducing complexity of flow management and pilots by facilitating execution of continuous descents at near-idle power settings.

The Study Team removed many of the rarely used enroute transitions and adjusted several of the remaining transitions to increase routing flexibility for arriving aircraft. They improved runway transitions, in some cases raising them to a higher altitude to provide for more efficient descent profiles that were also deconflicted from nearby departures. Most of the STARs now extend to about 200 nautical miles (nm) from IAH and HOU, with the longest procedures that support long-range flights arriving from the northeast reaching 400 nm.

Proposed changes to departure procedures also focused on PBN solutions that minimize flow interaction and level-off requirements, and facilitate execution of unrestricted climbs through the TRACON airspace. SIDs now extend to approximately 100 nm from IAH and HOU, and include additional enroute transitions that increase routing flexibility

[2] By providing the same routing options to conventional and PBN-capable aircraft, dual-use procedures decrease complexity of traffic management in an environment with mixed performance capabilities.

for departing aircraft. The Study Team designed RNAV SIDs that include runway transitions except for a few instances where controllers preferred to maintain flexibility by using vectors over alternative fixed paths.

Each of these changes addressed a specific problem identified by controllers and operators, and contributed toward an integrated solution focused on improving system and flight efficiency of Houston Metroplex operations. For the service providers, the key benefits include improved predictability and repeatability of flown trajectories, and reduced need for holding and vectoring. For the operators, key benefits include reduced time in level-flight below top of descent (TOD) and sometimes also reduced distance flown by aircraft as they transition between the enroute and approach, or between the takeoff and en route phases of flight.

METHODOLOGY AND FINDINGS

This analysis focuses on the quantitative benefits of Houston Metroplex improvements that can be estimated using surveillance and Airline Service Quality Performance (ASQP) data along with facility-reported arrival and departure rates. We analyzed and compared performance outcomes observed during a six-month period prior to implementation with those observed during an analogous period after implementation. We reported overall performance impacts together with changes in other factors that may have affected outcomes, and if feasible, contribution of these factors to overall changes in performance. The pre-implementation study period included operations between July 1 and December 31, 2013, while the post-implementation study period included operations between July 1 and December 31, 2014. June 2014 was excluded from the analysis as an initial "burn-in" period during which controllers and operators adjusted to the new environment and operations.

We worked with surveillance data collected by the FAA's Performance Data Analysis and Reporting System within the Fort Worth (ZFW) and Houston (ZHU) ATC centers. This dataset distinguishes flight plan and positional information reported by individual flights, which we used to evaluate characteristics of their lateral and vertical profiles, and corresponding flight efficiency. Overall time and distance represented indicators of horizontal flight efficiency, while Time and Distance in Level-Flight[3] and Time Weighted Altitude[4] (TWA) were indicators of vertical flight efficiency. Vertical flight efficiency indicators also revealed whether a flight was able to maintain a continuous descent profile below its TOD[5] until about 30 nm from the destination airport. Due to a close proximity of the two airports that necessitates use of altitude restrictions to separate approaches and takeoffs, subject-matter experts from I90 and ZHU believed it would be unreasonable to expect continuous descent profiles all the way to touchdown. Since most initial approach fixes are located around 30 nm from the two airports, we assumed that a flight executed continuous descent if it had no level-segments between TOD and a 30 nm ring around the destination airport.

Because TBFM adaptation was still ongoing well into the post-implementation study period, our study did not consider TBFM-related impacts. In an effort to focus the analysis on operations that were most directly affected by Metroplex improvements, we excluded nighttime operations[6] and operations conducted by military, helicopter and piston-engine aircraft. We also excluded extreme outliers[7] in performance from both study periods because they were representative of rare and unusual behavior and operating conditions as opposed to being caused by the Houston Metroplex improvements. Due to the difficulty of identifying discrete time periods of extreme weather occurring in the Metroplex area, and attributing unusual behavior of specific flight trajectories to that weather with a high degree of confidence, we opted not to base our exclusion of flights specifically on weather.

Also, our comparison of performance outcomes before and after implementation of Houston Metroplex improvements was limited to like-flights, which we classified by determining aircraft type, flight range, key flow, and runway configuration used for takeoff or landing. All of the aggregated findings represent average values of the same performance indicator weighted by contributing operations at individual airports or overall Metroplex. This was necessary to prevent wrong conclusions that could be influenced by substantial differences in performance of flights with different characteristics, excessive contribution of any particular group of flights or excessive outliers in performance.

[3] Consistent with other PBN analyses, an aircraft is considered to be in level-flight if it remains within 200 feet of the same altitude for 50 seconds or longer.

[4] For an aircraft, Time Weighted Altitude (TWA) is the average of all altitudes that the aircraft spent in level-flight below TOD weighted by the proportion of overall time in level-flight spent at each altitude. Rather than focusing on only duration or altitude of step-descents, TWA accounts for both and provides a standardized means for comparing descent profiles of flights with different step-descents.

[5] Top of descent (TOD) is the point at which an aircraft transitions from the cruise to the descent phase of flight. Unfortunately, it is not empirically reported and has to be estimated using surveillance data. Ideally at the end of the level- segment spent at the highest altitude during a flight, TOD is sometimes difficult to determine because of various restrictions that may require the aircraft to descend to a lower flight-level while still in cruise. An example is avoiding turbulence or complying with inter-facility agreements used to regulate complex flow interactions.

[6] To determine nighttime hours, we used the FAA's reporting requirement for IAH: 0700 to 2159 local time. For more information, please visit http://www.faa.gov/nextgen/snapshots/airport/.

[7] Extreme outliers were flights with extremely long flown distance relative to their GCD within each of the key flows. Approximately 2 percent of the flights within each flow turned out to be extreme outliers. Quick analysis of occurrences of severe weather events in this region showed that almost all of these flights happened during periods with bad weather before and after implementation.

We parsed flight plans to determine origin, destination and aircraft type for each of the flights, which we grouped according to their flight ranges represented by the great-circle distance between their origin and destination: long range (longer than 300 nm), medium range (150-300 nm) and short range (shorter than 150 nm). Long-Range flights had the opportunity to fly the full length of most of the published procedures, while other flights did not generally need enroute transitions and procedure segments that were farther away from IAH and HOU. Our analysis focused on the portion of trajectory flown within 300 nm from the two airports. This usually comprises final stages of cruise and complete descent and approach phases for the long-range flights, and included entire trajectories for medium- and short-range flights.

Key flows helped us determine the direction of flight relative to the airport's corner posts and merging fixes. Generally different for the two major airports in the Metroplex, these were dominated by procedures and enroute transitions (Figure 2). Finally, to provide for proper comparison of significantly different approach paths that the flights within the same key flow may have during periods with different runway configurations, we used surveillance position reports in the vicinity of IAH and HOU to determine runways used for landing and takeoffs.

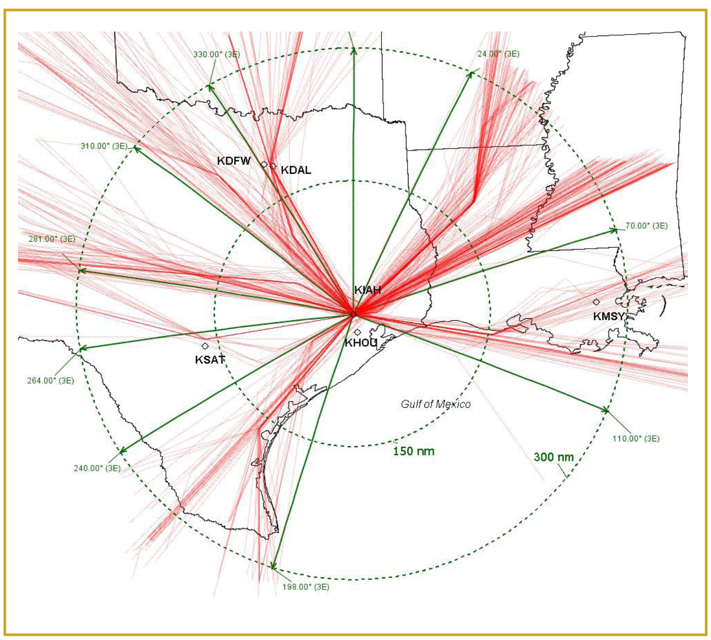


Figure 2 – IAH Key Flows and Sample Trajectories

AIRPORT EFFICIENCY

Changes in airport capacity are difficult to evaluate in the real world due to their sensitivity to dynamic operating conditions including weather, runway configuration and fluctuating demand. To overcome these challenges and facilitate understanding of capacity-related changes across National Airspace System airports, the FAA typically uses Airport

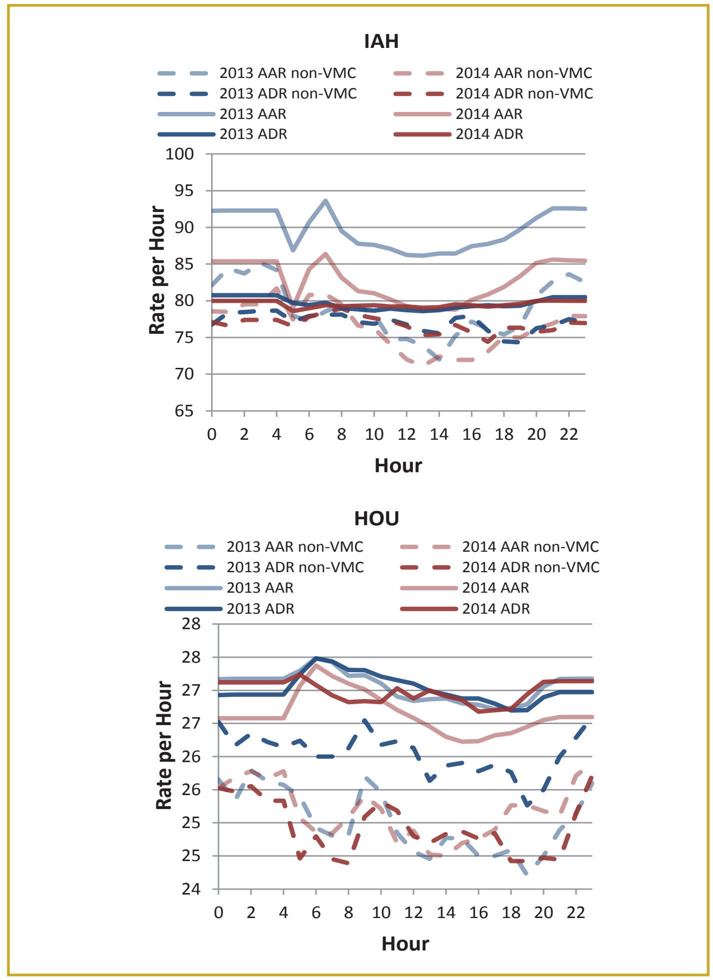


Figure 3 – Average Hourly AARs and ADRs at HOU and IAH

Departure Rates (ADR) and Airport Arrival Rates (AAR). These rates, also referred to as called rates, are determined by airport facilities as the number of arrivals and departures that each facility can handle for every hour of the day and is based on the expected operating conditions including weather, demand characteristics and ATC staffing.

After implementation of Houston Metroplex improvements, average hourly AAR decreased and ADR remained constant at IAH, while both rates remained constant at HOU (Figure 3). This is not surprising because facility-reported rates are rarely updated immediately after a new capability becomes available. Mostly driven by safety concerns and precaution, air traffic controllers need time to adjust to the new opportunities, limitations and ways of operating in the same region. For that reason, we also evaluated hourly throughput rates and investigated changes in high-end or peak hourly throughput rates as yet another proxy of airport capacity. This measure helped us to understand changes in airport ability to accommodate demand during peak periods, which is an indicator driven less by precaution and more by performance that is possible to achieve during high-pressure situations.

Peak airport throughput increased by 3.5 percent for arrivals and 9.4 percent for departures at IAH. During instrument

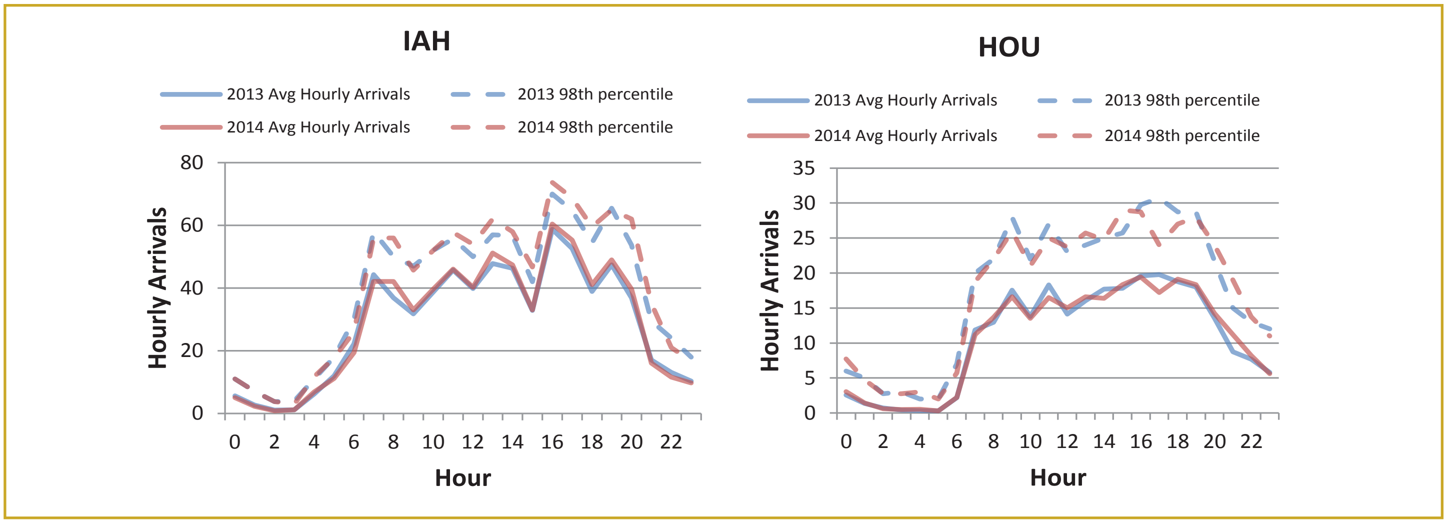


Figure 4 – Arrival Throughput at IAH and HOU

meteorological conditions (IMC) at IAH, the increase in peak throughput was much more substantial—10.2 percent for arrivals and 24.9 percent for departures. At HOU, the changes in peak airport throughput were negligible overall but apparent during IMC, when the arrival throughput rates increased by 9 percent and the departure rate increased by 32.6 percent (Figure 4).

Finally, we also needed to ensure that the increase in peak throughput was not caused by increased demand, as opposed to improved ability to run more efficient operations. For this reason, we evaluated average daily operations count as a proxy for demand, which increased by 2 percent at IAH and remained unchanged at HOU after implementation of Houston Metroplex improvements (Figure 5). Since the peak throughput increased more than overall demand, we can conclude that IAH is now able to accommodate more traffic during peak periods. During IMC, IAH now accommodates almost three more arrivals per hour and seven more departures per hour. Although overall peak throughput at HOU did not change, it increased by about three operations per hour during IMC. These numbers indicate increased airport capacity after recent implementations of Houston Metroplex improvements.

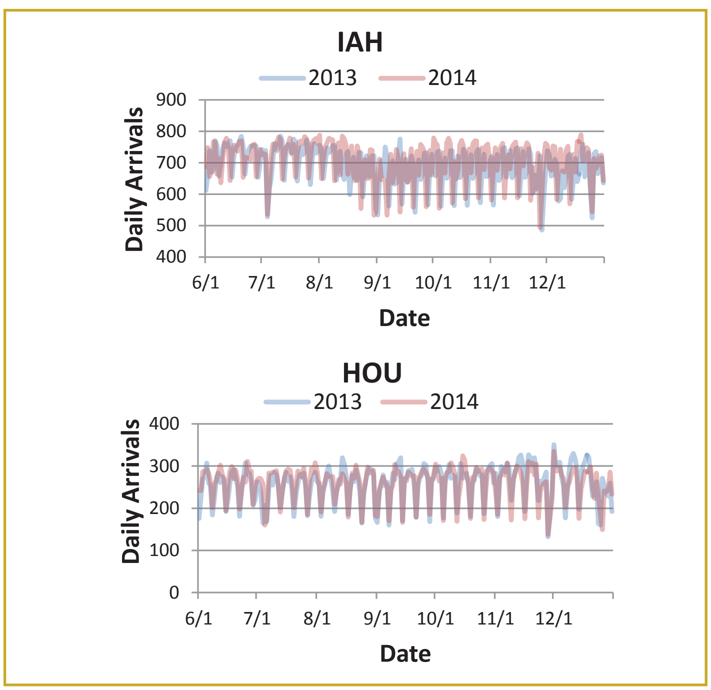


Figure 5 – Arrival Demand at IAH and HOU

FLIGHT EFFICIENCY

The sections below discuss overall flight efficiency-related impacts for arrivals and departures as well as separately by flight range.

ARRIVALS TO IAH AND HOU

Overall horizontal efficiency changed little after implementation. Distance flown for arrivals into IAH increased about 0.4 percent, while distance flown into HOU increased by 1.6 percent. However, significant vertical efficiencies were observed in the data as the rate of Continuous Descent Operations (CDO) into IAH and HOU more than tripled. Distance in level-flight increased on average 4 percent for arrivals into IAH and HOU, but this increase occurred at about 2,400 feet higher altitudes on average for IAH arrivals and over 2,000 feet higher altitudes on average for HOU arrivals.

CONTINUOUS DESCENT OPERATIONS

Because one of the key goals of Houston Metroplex improvements was to facilitate continuous descents into IAH and HOU, all flight trajectories were examined specifically in terms of the changes in their descent profiles and TOD locations.

After implementation of the Houston Metroplex improvements, arrivals finished cruising and started descending almost 12 nm or 12 percent closer to the two airports on average. This translates into longer cruise and shorter descent phases of flight, meaning longer time and distance spent at higher, more fuel-efficient altitudes,

Table 1 – Horizontal Efficiency for Flights Executing Continuous Descents

CDOs	Continuous Descent Operations				Distance (nm)			Time (minutes)		
	Operations		2014		2013	2014	Change	2013	2014	Change
IAH	12,048	(15%)	35,318	(42%)	146	133	-8.9%	27	25	-7.5%
HOU	1,834	(9%)	7,568	(36%)	141	129	-8.5%	27	25	-9.0%
Houston	13,882	(13%)	42,886	(41%)	145	132	-9.0%	27	25	-7.8%

Table 2 – Horizontal and Vertical Efficiency for Flights not Executing CDO

Non-CDOs	Distance (nm)			Distance in Level-Flight (nm)			Time-Weighted Altitude (feet)		
	2013	2014	Change	2013	2014	Change	2013	2014	Change
IAH	161	162	1.0%	22	24	9.6%	15,299	18,121	2,822
HOU	160	168	5.3%	22	30	37.8%	13,565	18,013	4,447
Houston	160	164	1.9%	22	25	15.2%	14,942	18,099	3,157

and consequently more efficient flight profiles. Since the implementation of Houston Metroplex improvements, arrivals executing continuous descents spent about 13 nm and two fewer minutes below TOD (9 and 8 percent improvements, respectively). More importantly, the proportion of arrivals executing continuous descents between TOD and the approach phase of flight more than tripled – from 13 to 41 percent of all arrivals to the two airports (Table 1).

Impacts on flights with step descents were mixed (Table 2), with their TODs about 2 nm or 2 percent farther away from the two airports, and average time in level-flight below TOD three minutes or 15 percent longer. However, flights with step descents now level off at over 3,000 feet higher altitude on average.

APPROACHES TO IAH AND HOU

Impacts on flight efficiency within 30 nm of the two airports were mixed, reflecting the complexity of interactions in the approach environment. Horizontal efficiency decreased slightly, with distance and time inside 30 nm of the two airports increasing just over 1 percent. On the other hand, vertical efficiency increased, with distance in level-flight within 30 nm decreasing by almost 26 percent. IAH arrivals flew on average 3.4 fewer nm and HOU arrivals 6.4 fewer nm in level flight after Houston Metroplex implementation. However, level-segments are now flown at lower altitudes on average – over 500 feet or 11 percent for IAH arrivals, and over 1,200 feet or 22 percent for HOU arrivals.

LONG-RANGE ARRIVALS

Horizontal efficiency of long-range flights within 300 nm of the two airports remained roughly the same after implementation of Houston Metroplex improvements, with no change in distance and time for IAH arrivals and only a minor increase in distance for HOU arrivals.

On the other hand, vertical flight efficiency improved considerably. Forty-three percent of arrivals to IAH and 37 percent of arrivals to HOU now fly the more fuel-efficient, continuous descent profiles. In addition, flights that still execute step descents experience fewer and higher level-offs, about 2,200 feet higher on average (Figure 6).

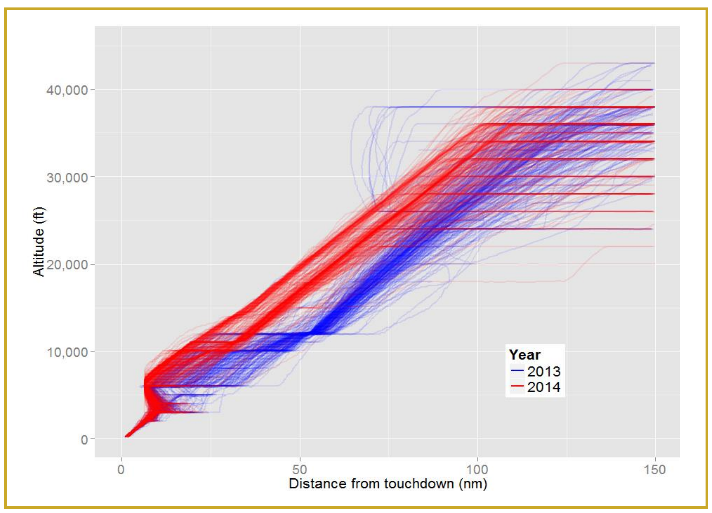


Figure 6 – A Sample of Vertical Profiles for Long-Range Arrivals to IAH via the Northeast Key Flow

The 6 nm average increase in distance in level-flight within 300 nm of the two airports is not a representation of longer step descents but longer cruise phase of flight. TOD is now considerably closer to the destination airports. In addition, the ratios of the changes in distance and time suggest that these level segments generally occur during flight segments involving higher airspeeds and higher altitudes, further implying cruise phase of flight.

MEDIUM-RANGE ARRIVALS

About half of all arrivals that originated at airports between 150 and 300 nm of IAH and HOU were flights from Dallas/ Fort Worth International Airport (DFW), Dallas Love Field (DAL), San Antonio International Airport (SAT) and Louis Armstrong New Orleans International Airport (MSY) (Figure 7). The remaining medium-range flights originated at dozens of smaller airfields scattered throughout the Metroplex, most of which generated insufficient demand for reliable patterns in behavior to be noticeable. Therefore, we examined all of them as a separate group, Other Medium-Range Airports.

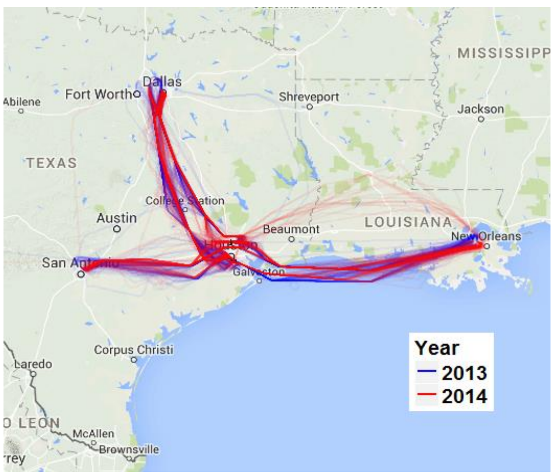


Figure 7 – A Sample of Lateral Trajectories of Medium-Range Arrivals to IAH and HOU

Compared to before implementation of Houston Metroplex improvements, trajectories of most medium-range arrivals are now between 2 and 6 nm and up to a minute longer on average. Arrivals from SAT are an exception, with average distance and time savings of 3 nm and 41 seconds (Table 3).

As with the long-range arrivals, vertical efficiency of medium-range arrivals to IAH and HOU improved in almost all cases (Figure 8). Step descents were used significantly less across the board, with 41 percent of all medium-range arrivals now being able to execute continuous descents below TOD. In addition, arrivals with step descents now level off at 1,948 feet higher altitudes on average.

While distance in level-flight for medium-range arrivals to IAH and HOU increased about 5 nm on average, TOD is now closer to the destination airports too, on average 13 nm closer for the arrivals executing CDOs and 4 nm closer for the arrivals with step descents. Therefore, this increase in distance and time in level-flight, or a significant proportion of it, is absorbed at cruise-altitudes and prior to initiating descent, resulting in less intense fuel burn.

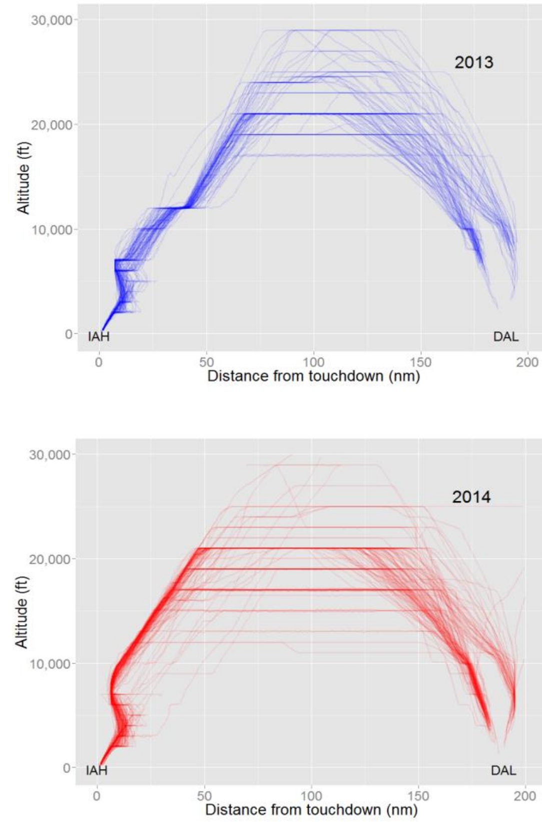


Figure 8 – A Sample of Vertical Profiles for IAH Arrivals from DAL

Arrivals from SAT experienced the highest improvement in overall flight efficiency with about 3 nm shorter average distance, unchanged average distance in level-flight--1,223 feet higher average altitude of step-descents--and almost quadrupled proportion of flights executing continuous descents (55 percent of arrivals from SAT now compared to the previously observed 14 percent).

Arrivals to HOU from MSY followed closely behind, with slightly increased horizontal efficiency and a more significant increase in vertical flight efficiency. Execution of continuous descents increased from 19 to 72 percent of arrivals from MSY, and average altitude of step-descents is now over 4,000 feet higher (Figure 9). However, note the trade-off between these two indicators of vertical flight efficiency and distance in level-flight, which increased by 6 nm on average. The average distance flown below TOD decreased by about 10 nm or 7 percent.

Next, arrivals from DFW experienced even more pronounced trade-offs in performance: on average, distance flown and altitude of step descents increased by 2 nm and 1,993 feet, respectively, while the distance in level-flight decreased 6 nm. Moreover, the proportion of flights executing continuous descents is now three times higher (43 percent of arrivals from DWF compared to 14 percent observed in the past), and TOD is on average 1.4 nm closer to the destination airports.

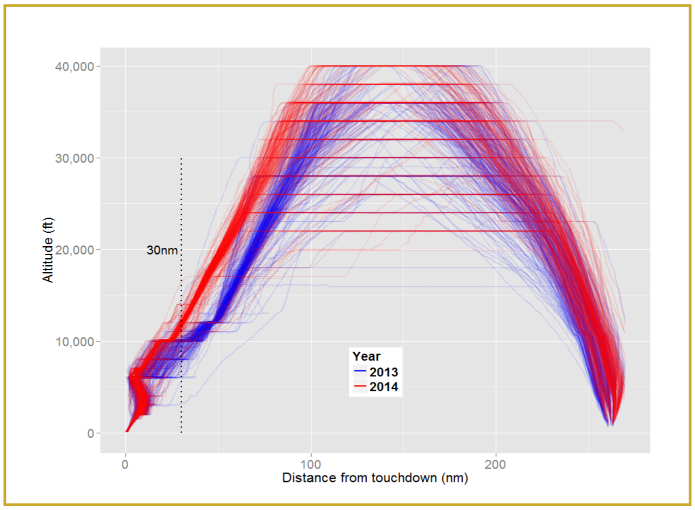


Figure 9 – A Sample of Vertical Profiles for HOU Arrivals from MSY

Finally, arrivals from DAL experienced the highest negative impact among the medium-range flights. However, despite the negative impacts in terms of increased distances and increased distances in level-flight, continuous descents are more frequent even among these flights—16 percent compared to 4 percent of arrivals from DAL prior to Metroplex improvements. Step-descents now occur at higher altitudes on average—16,584 feet compared to 15,311 feet observed in the past.

SHORT-RANGE ARRIVALS

With about 40 percent of all short-range arrivals to IAH and HOU, Austin-Bergstrom International Airport (AUS) was the only airport within 150 nm of the two major airports that generated significant demand. Other short-range flights, originating from numerous minor airfields scattered throughout the region, were too infrequent for reliable patterns in behavior to be noticeable and too dissimilar from each other for a meaningful grouping to be possible. Therefore, our analysis and findings for short-range arrivals are limited to flights originating from AUS.

Horizontal efficiency of arrivals from AUS improved slightly overall. However, while the average distance increased by about 2 percent for arrivals to HOU, it also decreased by 1.3 percent for arrivals to IAH. The average times for these flights reflect the same trend.

Vertical efficiency improved, although less considerably compared to the long-range and medium-range arrivals: an additional 4 percent of AUS arrivals to IAH and 1 percent of AUS arrivals to HOU now execute continuous descents (Table 4). Although slight, average distance decreased by 0.8 percent and time in level flight by 0.5 percent. This was not a surprise because such short flights generally have low cruise altitudes and little opportunity for improvement of their descents. However, average altitude of step-descents increased about 1,100 feet for flights to IAH and HOU.

DEPARTURES FROM IAH AND HOU

Runways 15L and 15R are dominant departure runways at IAH used about 90 percent of the time. Although runways 12L and 12R are dominant runways at HOU—used about 80 percent of the time—runways 30L, 30R and 04 also are frequently used by flights heading to the Dallas metropolitan area. Therefore, our analysis focuses on flights taking off from dominant departure runways at the two airports, and departures of 30L, 30R and 04 at HOU.

Horizontal and vertical flight efficiency within 300 nm of IAH and HOU decreased across all departures from the two airports, with greater impacts on departures from IAH (Tables 5 and Table 6). On average, distance and time within 300 nm of IAH and HOU increased 0.4 percent and 1.1 percent, while distance and time in level-flight increased by 4 and 5.5 percent respectively, and the average altitude of level-segments decreased by over 700 feet.

LONG-RANGE DEPARTURES

Horizontal efficiency of long-range departures within 300 nm of IAH and HOU remained about the same after implementation of Houston Metroplex improvements (Table 6 and Figure 10), while vertical flight efficiency decreased across the board: the average distance and time in level-flight increased 4 and 5.7 percent, respectively, and the average altitude of level-segments decreased about 1,000 feet (Table 5). The impact was more significant for departures from IAH and barely noticeable for departures from HOU.

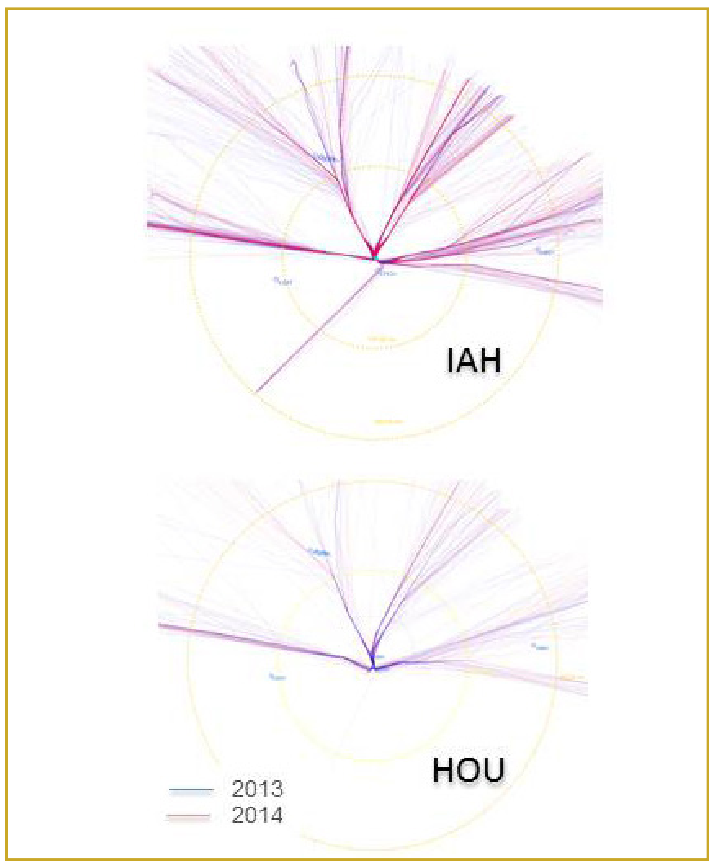


Figure 10 - Key Departure Flows and a Sample of Long-Range Departures from IAH and HOU

Table 3 – Vertical Efficiency within 300 nm of IAH and HOU: Arrivals

		Continuous Descent Operations		Distance in Level-Flight (nm)			Time in Level-Flight (minutes)			Time-Weighted Altitude (feet)		
Origin	Dest.	2013	2014	2013	2014	Change	2013	2014	Change	2013	2014	Change
Any	IAH	14%	43%	187	194	3.6%	28	28	1.4%	28,583	30,896	2,313
Any	HOU	8%	37%	191	193	1.0%	30	29	-2.7%	30,612	32,717	2,105
Long-Range		13%	41%	188	194	3.0%	28	28	0.4%	29,023	31,271	2,248
DFW	IAH	17%	53%	70	65	-7.6%	12	11	-11.3%	15,073	17,560	2,487
	HOU	0%	2%	75	64	-14.5%	13	11	-12.7%	15,027	14,935	(92)
Houston-DFW		14%	43%	71	66	-7.4%	12	11	-11.6%	15,064	17,057	1,993
DAL	IAH	16%	64%	76	95	25.0%	13	15	18.4%	14,795	16,529	1,734
	HOU	1%	2%	61	61	0.5%	11	11	-1.5%	15,435	16,599	1,164
Houston-DAL		4%	16%	64	69	7.6%	11	12	4.2%	15,311	16,584	1,273
SAT	IAH	4%	60%	70	70	0.1%	14	14	-2.3%	11,880	14,148	2,267
	HOU	33%	45%	54	55	1.8%	9	10	1.4%	16,569	15,870	(699)
Houston-SAT		14%	55%	65	65	1.1%	12	12	-0.7%	13,474	14,696	1,223
MSY	IAH	26%	33%	106	112	6.4%	19	19	5.0%	19,623	21,321	1,698
	HOU	19%	72%	88	94	6.5%	15	15	0.5%	22,952	27,390	4,438
Houston-MSY		23%	49%	98	105	7.1%	17	18	3.9%	21,114	23,837	2,723
Other Apts.	IAH	9%	47%	118	124	5.5%	19	19	3.0%	17,727	20,046	2,319
	HOU	21%	33%	83	84	0.8%	15	15	0.1%	17,883	18,816	933
Houston – Other Airports.		12%	44%	110	115	4.8%	18	19	2.5%	17,763	19,768	2,005
Medium-Range		12%	41%	91	95	4.4%	16	16	1.7%	17,023	18,971	1,948
AUS	IAH	34%	38%	44	45	0.7%	9	9	2.1%	10,468	11,736	1,268
	HOU	2%	3%	56	55	-0.5%	11	10	-2.2%	10,791	11,763	972
Short-Range		12%	41%	91	95	4.4%	16	16	1.7%	17,023	18,971	1,948
Houston Overall		13%	41%	163	170	4.0%	25	25	1.3%	25,899	28,218	2,319

Table 4 – Horizontal Efficiency within 300 nm of IAH and HOU: Arrivals

		Arrivals		Distance (nm)			Time (minutes)		
Origin	Dest.	2013	2014	2013	2014	Change	2013	2014	Change
Any	IAH	72,989	79,655	327	327	0.0%	52	52	0.3%
Any	HOU	20,208	20,660	328	331	0.8%	54	54	-0.9%
Long-Range		93,197	100,315	327	328	0.2%	52	52	0.0%
DFW	IAH	2,643	2,684	219	221	0.8%	39	39	0.4%
	HOU	620	636	244	246	0.8%	44	44	-0.4%
DFW-Houston		3,263	3,320	224	226	0.8%	40	40	0.3%
DAL	IAH	912	1,064	211	216	2.4%	39	40	2.4%
	HOU	3,800	3,760	234	240	2.6%	41	42	2.4%
DAL-Houston		4,712	4,824	229	235	2.3%	41	42	2.2%
SAT	IAH	1,865	1,748	195	191	-1.8%	38	38	-2.3%
	HOU	960	817	184	180	-2.4%	35	34	-1.5%
SAT-Houston		2,825	2,565	191	188	-1.9%	37	37	-1.8%
MSY	IAH	1,969	2,154	292	294	0.8%	53	53	0.2%
	HOU	1,598	1,525	298	297	-0.2%	53	52	-2.1%
MSY-Houston		3,567	3,679	295	295	0.3%	53	53	-0.7%
Other Airports	IAH	10,279	10,622	261	262	0.6%	45	46	0.8%
	HOU	3,085	3,106	235	238	1.3%	45	46	1.4%
Other Apts.-Houston		13,364	13,728	255	257	0.8%	45	46	0.9%
Medium-Range		27,731	28,116	245	248	1.1%	44	44	0.8%
AUS	IAH	1,803	1,855	152	150	-1.3%	31	30	-1.3%
	HOU	1,138	955	149	152	2.1%	30	30	1.2%
Short-Range		2,941	2,810	151	151	-0.1%	30	30	-0.3%
Houston Overall		123,869	131,241	305	307	0.7%	50	50	0.4%

Table 5 – Vertical Efficiency within 300 nm of IAH and HOU: Departures

		Distance in Level-Flight (nm)			Time in Level-Flight (minutes)			Time-Weighted Altitude (feet)		
Origin	Dest.	Level - flight (nm)	2014	Change	2013	2014	Change	2013	2014	Change
IAH	Any	144	152	5.5%	19	20	7.6%	32,375	31,103	(1,273)
HOU	Any	172	173	0.5%	24	24	1.3%	37,052	36,926	(126)
Long-Range		151	157	4.0%	20	21	5.7%	33,566	32,563	(1,003)
IAH	DFW	81	79	-2.2%	13	13	-3.4%	18,101	19,256	1,155
HOU		78	76	-2.3%	13	12	-3.5%	19,292	20,354	1,062
Houston-DFW		80	78	-1.8%	13	13	-3.0%	18,498	19,516	1,018
IAH	DAL	73	86	19.3%	13	15	18.0%	14,020	14,581	561
HOU		73	73	-0.9%	13	13	-0.9%	18,148	19,493	1,345
Houston-DAL		73	78	6.3%	13	13	5.8%	16,379	17,760	1,381
IAH	SAT	61	85	37.7%	12	15	32.4%	16,558	17,237	679
HOU		83	84	0.8%	16	16	-0.1%	17,140	16,380	(760)
Houston-SAT		68	84	23.3%	13	16	20.6%	16,739	16,727	(12)
IAH	MSY	79	74	-6.5%	12	11	-7.8%	23,671	24,022	351
HOU		71	76	6.3%	10	11	4.8%	28,225	28,390	166
Houston-MSY		76	75	-0.9%	11	11	-2.2%	25,815	25,932	117
IAH	Other Apts.	77	78	1.7%	12	13	4.2%	19,260	18,735	(525)
HOU		87	88	0.8%	16	16	-0.3%	21,477	21,158	(319)
Houston – Other Airports		79	81	2.0%	13	14	4.2%	19,742	19,365	(377)
Medium-Range		77	79	2.9%	13	13	3.1%	19,900	20,129	1.1%
IAH	AUS	35	35	0.2%	7	7	1.1%	10,392	10,700	308
HOU		45	45	-1.1%	9	9	-0.5%	13,329	12,952	(377)
Short-Range		39	39	-1.1%	8	8	-0.2%	11,652	11,610	(42)
Houston Overall		135	141	4.0%	19	20	5.5%	30,570	29,854	(716)

Table 6 – Horizontal Efficiency within 300 nm of IAH and HOU: Departures

		Departures		Distance (nm)			Time (minutes)		
Origin	Dest.	2013	2014	2013	2014	Change	2013	2014	Change
IAH	Any	73,688	75,273	308	308	-0.1%	45	45	0.5%
HOU	Any	25,162	25,193	309	310	0.1%	45	46	0.8%
Long-Range		98,850	100,466	309	309	0.0%	45	45	0.6%
IAH	DFW	2,280	2,273	232	237	2.3%	41	44	6.3%
HOU		1,141	706	250	257	2.5%	45	47	5.3%
Houston-DFW		3,421	2,979	238	242	1.6%	43	45	5.1%
IAH	DAL	1,013	1,072	210	215	2.6%	40	41	4.0%
HOU		1,351	1,966	231	235	1.6%	43	44	2.9%
Houston-DAL		2,364	3,038	222	228	2.7%	41	43	3.8%
IAH	SAT	1,498	426	189	195	3.2%	38	40	4.2%
HOU		675	627	194	195	0.4%	41	41	0.0%
Houston-SAT		2,173	1,053	191	195	2.3%	39	40	3.4%
IAH	MSY	1,941	2,092	273	274	0.3%	47	47	-0.9%
HOU		1,727	1,626	274	274	0.2%	46	45	-0.2%
Houston-MSY		3,668	3,718	273	274	0.3%	46	46	-0.5%
IAH	Other	77	78	12	13	4.2%	19,260	18,735	(525)
Apts.		8,422	8,700	230	233	1.2%	41	42	3.3%
HOU		2,339	3,058	230	236	2.8%	45	46	2.6%
Medium-Range		22,387	22,546	234	239	2.2%	42	44	3.3%
IAH	AUS	1,727	1,726	133	137	3.0%	29	29	0.6%
HOU		1,298	1,170	144	145	0.6%	30	30	0.6%
Short-Range		3,025	2,896	138	140	1.8%	29	30	0.5%
Houston Overall		124,262	125,908	291	292	0.4%	44	45	1.1%

MEDIUM-RANGE DEPARTURES

Horizontal efficiency of medium-range departures decreased after implementation of Houston Metroplex improvements: the average distance and time are about 5 nm and two minutes longer (2.2 and 3.3 percent), respectively. Vertical efficiency outcomes were mixed, with generally increased or unchanged average distance in level-flight and average attitudes of step-climbs. However, departures to the Dallas metropolitan area now level off at just over 1,000 feet higher altitudes, indicating a general improvement in traffic flow deconfliction affecting these flights. Also, departures to DFW and MSY have shorter step-climbs on average and not only longer but also higher cruise segments. However, these localized improvements in vertical efficiency were smaller for departures to MSY and generally not as substantial as the improvements observed for arrival flows.

SHORT-RANGE DEPARTURES

With only a small increase in the average distance and average distance in level-flight, and a small decrease in the average altitude of step-climbs, IAH departures to AUS experienced an insignificant change in performance. The direction of change is exactly opposite for the HOU flights to AUS but equally insignificant (Table 5 and Table 6).

PROCEDURE UTILIZATION

Empirical data capturing the use of procedures is archived only for voice recordings, which cannot be effectively processed for long periods of time. Therefore, we developed a complex in-house tool to estimate procedure utilization by analyzing conformance of the flown trajectories to the published procedures. For a flight, we determine conformance as the extent to which its trajectory overlaps with the procedure specified in the last flight plan or amendment that was filed prior to it joining the procedure. We do not check for conformance against the whole procedure, but only between an arrivals' joining waypoint that was specified in the flight plan and the first waypoint on its approach path. For departures, we determine conformance between a departure's first waypoint and the last waypoint on the transition specified in the flight plan.

To investigate utilization of procedures as a function of flow density across the Metroplex, we also developed a tool that determines utilization of individual segments on a procedure relative to the overall arrival traffic requesting to fly the procedures, and provides a spatial illustration of the segment utilization across the region. The tool determines procedure segments as sections of each procedure between their consecutive waypoints excluding runway transitions. We assumed that an aircraft flew over a segment if it conformed to 80 percent of that segment length (Figure 11).

IAH has a higher number of available RNAV STARs, with the proportion of flights requesting a particular procedure ranging between 5 and 20 percent. HOU arrivals, on the other hand, have fewer available procedures, with almost 60 percent of flights arriving from the northeast or northwest. Therefore,

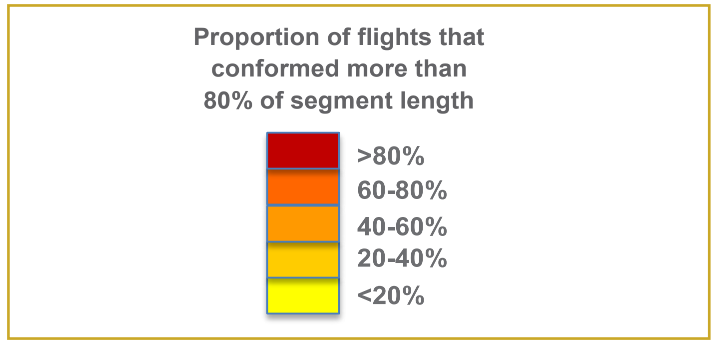


Figure 11—Color-coding for segment utilization

using a common scale to illustrate procedure utilization for the two airports is not possible. In general, the thicker the line, the greater the proportion of flights that requested the procedure, with dashed lines capturing even smaller proportion of flights that the full lines; however, the same line thickness indicates a different utilization level at the two airports.

Finally, the remaining analysis does not attempt to determine differences in procedure utilization before and after implementation of Houston Metroplex improvements, but simply investigate the utilization of currently available procedures.

AREA NAVIGATION STANDARD TERMINAL ARRIVAL ROUTES

STARs facilitate merging arrivals from several en route directions into a single stream leading to the landing runway. IAH operates in the west configuration about 60 percent of the time and 40 percent in the east configuration. The need for configuration-specific STARs at IAH is greater than at HOU, which operates in a southeast configuration more than 80 percent of the time. Consequently, RNAV STARs to IAH are configuration-specific and include runway transitions, while those to HOU are not.

Of the 17 new RNAV STARs, 12 support IAH and five support HOU operations. Demand for these procedures is high, with more than 95 percent of the arrivals to IAH and about 79 percent of the arrivals to HOU specifying the preferred RNAV STARs in their flight plans.

Almost all arrivals to IAH join an RNAV STAR within 250 miles of the airport, with most joining between 100 and 200 nm (Figure 12). Arrivals to HOU join the procedures closer to the airport, typically between 50 and 175 nm of HOU. Procedure conformance is high across the board, with roughly 60 percent of arrivals conforming for more than 70 percent of the filed procedure portions, and about half of all arrivals conforming for more than 90 percent of the filed procedure portions.

Not surprisingly, the most heavily utilized segments of RNAV STARs are the ones closer to IAH and HOU (Figure 13) as aircraft are increasingly merged and sequenced for approach

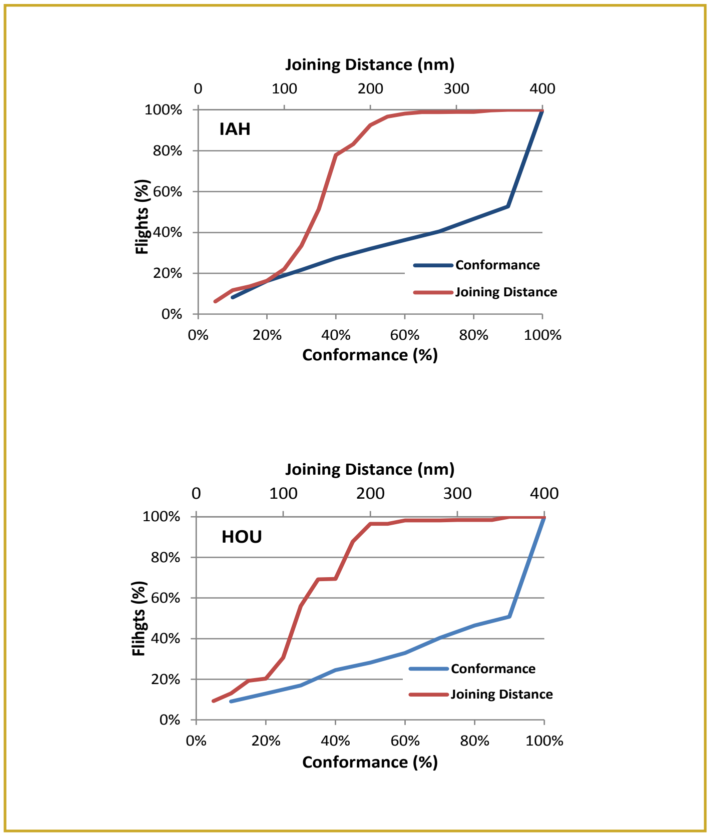


Figure 12 – Utilization of RNAV STARs by Conformance and Joining Distance

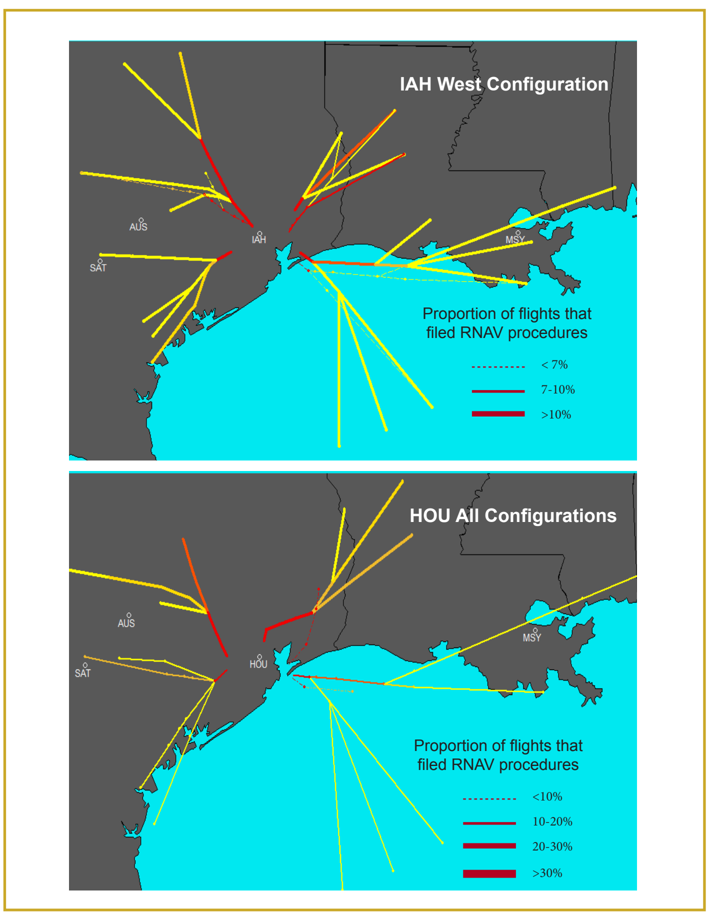


Figure 13—IAH and HOU RNAV STAR Utilization

to a limited set of runways. In addition, more traffic arrives from the northwest and northeast, comprising 70-80 percent of total arriving traffic, resulting in higher potential demand for the procedures typically serving these flows.

RNAV STANDARD INSTRUMENT DEPARTURES

The key purpose of RNAV SIDs is to safely and expeditiously facilitate moving departures away from their origins, merge them into the overhead streams and transition them to the en route sectors. Unlike STARs, which facilitate merging arrivals from several en route directions into a single stream leading to the landing runway, departing flights often fan out in less concentrated flows and varying directions immediately after takeoff. As a result, conformance to SID segments typically increases farther away from the departing runways.

Unlike the RNAV arrival procedures, the departure procedures are not configuration-specific at either of the two airports. Of the 20 new RNAV SIDs, 10 procedures support IAH and 10 support HOU operations, with the two airports sharing six of the procedures.

Most departures from IAH and HOU join a SID somewhere between 100 and 150 nm of the origin, and just a few, less than 10 percent, join closer than 50 nm (Figure 14). About 30 percent of departures from IAH and only 15 percent of departures from HOU conform to more than 80 percent of the procedure after the joining waypoint. In addition, about 40 percent of departures from IAH and over half of departures from HOU conform to less than 10 percent of the procedures.

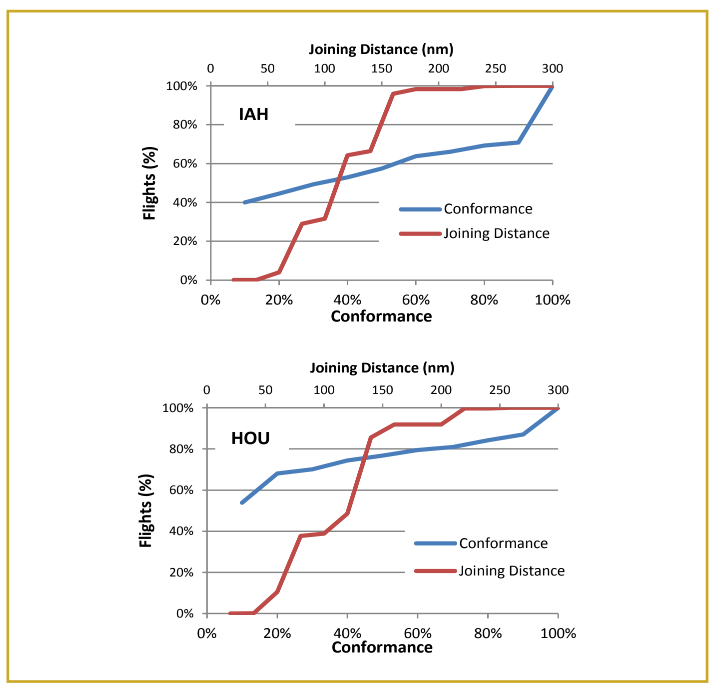


Figure 14 – Utilization of RNAV SIDs by Conformance and Joining Distance

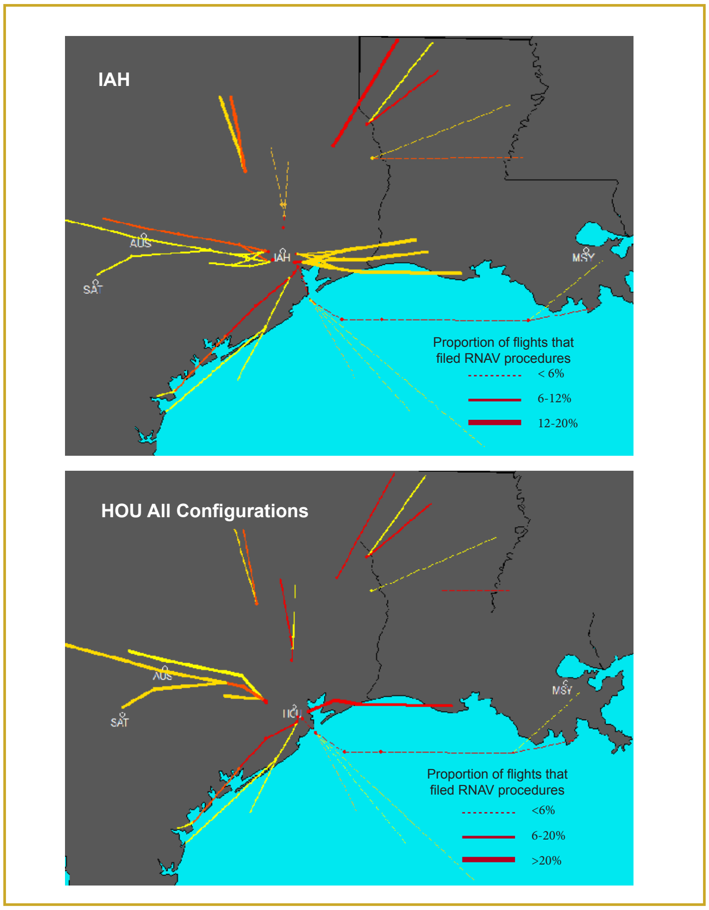


Figure 15—IAH and HOU RNAV SID Utilization

Compared to RNAV STARs, utilization of RNAV SIDs is generally lower, and increases for the segments that are farther away from IAH and HOU (Figure 15). Utilization of RNAV SIDs is especially low north of the two airports, most likely because of the interaction between the two airports and heavy use of vectoring.

SUMMARY

The FAA implemented multiple changes to the Houston Metroplex on May 29, 2014, the first key Metroplex. Houston Metroplex includes two major and 16 satellite airports, and a complex airspace consisting of segments controlled by two ATC center facilities, a major TRACON facility, and several Class D airspace units. Focused on operations at the two busiest airports, Houston Metroplex improvements incorporated minor airspace adjustments, publication of 49 new PBN procedures, modification of 11 existing procedures and elimination of 20 procedures. In addition, IAH and HOU traffic is now supported by the TBFM automation, which continues to be adjusted in response to the new routing structure and still developing operating practices.

In early 2015, MITRE Corp. completed a post-implementation review of Houston Metroplex improvements and determined an annual benefit of $6.1 million to the operators at the two largest airports in the area. This analysis complements MITRE's study by addressing additional impacts on aircraft ability to execute continuous descents and investigates impacts observed over a longer study period. We focused on operational and performance impacts, and did not attempt to monetize the corresponding savings.
Although average hourly AAR and ADR either decreased or remained fairly constant after implementation of Houston Metroplex improvements, IAH and HOU now accommodate more operations during peak hours. Since the peak throughput increased more than the overall demand, we can conclude that both airports are now able to run more efficient operations. IAH now accommodates about 10 more and HOU three more operations per hour during IMC. However, improved airport efficiency has not yet led to improvements in flight efficiency on the airport surface.

Trade-offs in flight efficiency were prominent for arrivals and departures. Although arrivals now fly up to 1.6 percent longer distances within 300 nm of the two airports, their cruise is longer and descent more efficient. On average, TOD is 12 nm closer to the two airports, and level-segments are around 4 percent longer and occur at about 2,400 feet higher altitudes for IAH arrivals and over 2,000 feet higher altitudes for HOU arrivals. Departures, on the other hand, fly up to 1.1 percent longer distances within 300 nm of the two airports, and experience a 4.0 to 5.5 percent longer cruise but also over 700 feet lower level-segments on average.

Because one of the key goals of Houston Metroplex improvements was to facilitate continuous descents into IAH and HOU, we investigated changes in descent profiles more carefully. Arrivals are more than three times more likely to execute continuous descents – the rate of CDOs increased from 13 to 41 percent of all arrivals to the two airports – with their TODs about 13 nm and two minutes closer to the two airports. Impacts on flights with step-descents were mixed, with their TODs about 4 nm farther away from the two airports and time in level-flight below TOD three minutes longer on average. However, flights with step-descents now level off at over 3,000 feet higher altitude on average too.

Arrivals from SAT are the biggest beneficiaries of improvements introduced through the Houston Metroplex project, with Average distance and time savings of 3 nm and 41 seconds, almost quadrupled proportion of flights executing continuous descents, and over 1,000 feet higher average altitude of level-segments.

RNAV STAR utilization is high across the board, with about half of all arrivals to IAH and HOU conforming for more than 90 percent of the filed procedure portions. Arrivals to IAH typically join an RNAV STAR between 100 and 200 nm, while arrivals to HOU join the procedures closer, typically between 50 and 175 nm, to the airport. Although departures generally join SIDs closer to the two airports, utilization of RNAV SIDs is lower because of a heavy use of direct-to clearances: about 30 percent of departures from IAH and 15 percent of departures from HOU conform to more than 80 percent of the procedure after the joining waypoint.

RECATEGORIZATION OF WAKE TURBULENCE CATEGORIES AND SEPARATIONS

Air traffic controllers in the United States use two classifications and sets of separation standards to prevent negative impacts of wake turbulence from nearby aircraft during approach and takeoff (Figure 1): traditional and recategorized wake classes (RECAT). While the traditional wake separation classes are based on maximum takeoff weight, the new RECAT categories also consider aircraft weight, the new RECAT categories also consider aircraft wingspan and approach speed, providing for a more accurate characterization the risk of wake encounters. As a result, separations for many combinations of aircraft categories can be safely reduced with RECAT, especially for those behind the traditional Heavy class and the Boeing 757 aircraft. (Table 1). Two key differences between the traditional and RECAT aircraft classification are:

- Aircraft previously classified as Heavy are split into Category B or C, and Large into Category D or E. Boeing 757 belongs to Category D, while Super and Small classes are renamed to Category A and F.
- Compared to the traditional classification, separation standards for most aircraft trailing Category C or D aircraft are shorter, while standards for Category F aircraft trailing most other aircraft are longer.

Reduced separations for many aircraft-pair combinations are likely to lead to tighter aircraft sequences and increased capacity and throughput during heavy demand periods

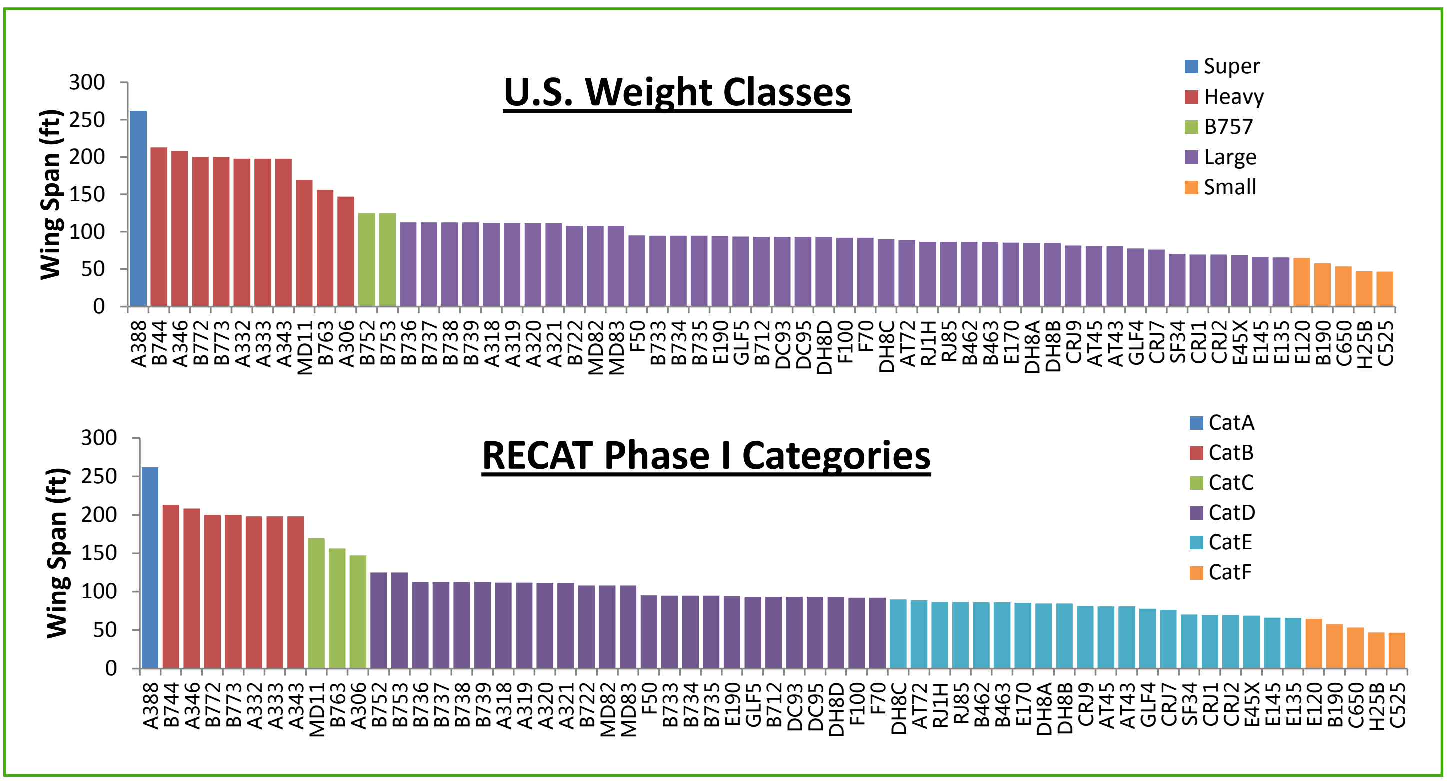


Figure 1 – Traditional and RECAT Phase 1 Categories by Aircraft Model

Table 1 – Separations* for Traditional and RECAT Aircraft Categories

Traditional Weight Classes	Follower				
	A380	Heavy	B757	Large	Small
A380	MRS	6.0	7.0	7.0	8.0
Heavy	MRS	4.0	5.0	5.0	6.0
B757	MRS	4.0	4.0	4.0	5.0
Large	MRS	MRS	MRS	MRS	4.0
Small	MRS	MRS	MRS	MRS	MRS

Recat Categories	Follower					
	A	B	C	D	E	F
A	MRS	5.0	6.0	7.0	7.0	8.0
B	MRS	3.0	4.0	5.0	5.0	7.0
C	MRS	MRS	MRS	3.5	3.5	6.0
D	MRS	MRS	MRS	MRS	MRS	5.0
E	MRS	MRS	MRS	MRS	MRS	4.0
F	MRS	MRS	MRS	MRS	MRS	MRS

FAA Order 7110.659, Table 5-5-2

No Change
Separation Decrease for Entire Category
Separation Decrease for Part of Category
Separation Increase for Entire Category
Separation Increase for Part of Category

*Values in the table represent separation requirements in nautical miles. MRS is Minimum Radar Separations.

at many of the airports where the new standard is used. Consequently, traffic flow will be more efficient on airport surfaces and in terminal areas. This results in shorter runway queues and taxi times for departures along with less holding, vectoring and time in terminal airspace for arrivals. Increased airport throughput also could encourage a change in use of airport resources, such as less frequent use of remote offload runways, which would further improve system and operator efficiency. Over time, these improvements may enable operators to adjust their schedules to better meet the needs of the flying public.

By the end of fiscal year 2015, the FAA authorized the use of RECAT separations at nine Terminal Radar Approach Control (TRACON) centers in the National Airspace System (NAS): Memphis (November 2012), Louisville (September 2013), Cincinnati (March 2014), Atlanta (June 2014), Houston (December 2014), Charlotte (March 2015), New York (March 2015) and Chicago (June 2015). In the past two annual NextGen performance assessment reports, we presented changes in operator and system performance after introducing RECAT at the first two locations in the NAS. This analysis builds on those two studies. It aims to determine commonalities and differences in post-implementation impacts, and benefits across locations at which RECAT use was authorized by the end of FY 2014. In addition, this analysis also attempts to provide insights into the sensitivity of overall benefits to local operating conditions, including fleet mix, carrier dominance and demand profile.

To better isolate direct impacts of RECAT use, we studied impacts during periods of peak demand, which are dominated by cargo operations of a single cargo operator at three of the four locations: FedEx at Memphis International Airport (MEM), UPS at Louisville International Airport (SDF) and DHL at Cincinnati/Northern Kentucky International Airport (CVG).

Unfortunately, cargo operators are not required to report Airline Service Quality Performance (ASQP) data, which includes information about airline on-time performance, flight delays and cancellations, so we determined changes in airport and flight efficiency by working only with facility-reported called rates and surface surveillance data (Table 2). Airport Departure Rates (ADR) and Airport Arrival Rates (AAR) are known as called rates and are determined as the number of arrivals and departures that each facility can handle for each hour of each day based on the expected operating conditions, including weather, demand characteristics and air traffic control staffing. Surface surveillance data is available for MEM and SDF but not for CVG (Table 4). As a result, only partial analysis of changes in performance at CVG was possible.

In contrast, traffic volume at Hartsfield–Jackson Atlanta International Airport (ATL) is high enough to allow for flights outside peak hours to also benefit from new aircraft categorization and separations. In addition, ATL has Airport Surface Detection Equipment-Model X (ASDE-X) surveillance, and most of the carriers operating at this airport report ASQP for their flights, so data available for this location was more detailed and complete compared to the other three locations.

We used the MITRE Corporation's ***threaded track*** data to measure inter-aircraft spacing, throughput, and arrival times in TRACON airspace[1], and the company's ***groundtracker*** tool to estimate departure queue and taxi-out times. We also used facility reported called rates to estimate airport capacity

[1] Threaded Track data is a fusion of National Offload Program and Traffic Flow Management System messages, and Airport Surveillance Detection Equipment-Model X (ASDE-X) surveillance data into smoothed representations of flight paths, altitudes and speeds.

Table 2 – RECAT Authorization Dates and Key Analysis Considerations by Location

Airport	Authorization Date	Analysis Period**		Key Available Data Sources	Focus of the Analysis
		Before	After		
MEM	Nov 1, 2012	Nov 1, 2011 - Oct 31, 2012	Nov 1, 2012 – Nov 30, 2013	Terminal and Surface Surveillance	Dep peaks: RWY 18L, 18R 03:45-06:15, Tue-Sat Arr peaks: RWY 36L, 36R 11:15-02:00, Tue-Sat
SDF	Sep 1, 2013	Oct 1, 2012 - Aug 31, 2013	Sep 1, 2013 – Nov 30, 2014	Terminal and Surface Surveillance	Dep peaks: RWY 17L, 17R 03:30-05:30, Tue-Sat Arr peaks: RWY 35L, 35R 11:15-02:15, Tue-Sat
CVG	Mar 11, 2014	Apr 1, 2013 – Aug 31, 2013	Apr 1, 2014 – Aug 31, 2014	Terminal Surveillance	Dep peaks: RWY 27 04:00-07:00, Tue-Fri Arr peaks: RWY 09 00:00-03:00, Tue-Sat
ATL	Jun 1, 2014	Jan 1, 2013 – May 31, 2014	Jun 1, 2014 – Nov 30, 2014*	Terminal and Surface Surveillance ASQP	Dep peaks: RWY 08R, 09L, 26L, 27R All day, Mon-Sun Arr peaks: RWY 08L, 09R, 10, 26R, 27L, 28 All day, Mon-Sun

** Due to a construction project on runway 08L/26R, the period between Sept. 15 and Oct. 14, 2014, was excluded from our analysis.*
*** Analysis of time in terminal airspace is included additional time periods.*

impacts and ASQP data to estimate flight efficiency impacts at ATL. In addition to studying changes in performance during hours with heavy demand, we paid special attention to periods with a significant presence of Heavy and Boeing 757 aircraft.

METHODOLOGY AND FINDINGS

Due to a decline in demand, daytime operations are rarely capacity constrained at MEM, SDF and CVG. However, nighttime operations dominated by cargo aircraft at these airports remained steady during the past few years and sufficiently dense to be affected by RECAT separations. Before midnight each weekday, large aircraft loaded with cargo for the overnight sort begin to arrive at MEM. They usually land on Runways 36L and 36R before proceeding to the FedEx facilities on the north side of the airport. These aircraft depart a few hours later, usually off Runways 18L and 18R. Similarly, UPS arrivals typically land on runways 35L and 35R at SDF, and the departures take off from Runways 17L and 17R. DHL arrivals usually land on Runway 09 at CVG, and the departures take off from Runway 27.

In ATL, overall demand also has declined since introduction of RECAT. However, operations remained sufficiently dense throughout the day to be affected by RECAT separations. During east flow, departures primarily take off from Runways 08R and 09L and arrivals land on Runways 08L and 09R, with occasional landings on Runway 10. In west flow, departures take off from Runways 26L and 27R and arrivals land on Runways 26R and 27L. Runway 28 is an overflow runway used as needed for departures and arrivals. However, to sustain operations during the closure of Runway 08L/26R between September 15 and October 15, 2014, Runway 08R/26L was used for arrivals and departures. To avoid any ambiguities that such an atypical configuration may introduce, we excluded this period from our analysis.

AIRPORT CAPACITY IMPACTS

AIRPORT DEPARTURE AND ARRIVAL RATES

Changes in airport capacity are difficult to evaluate in the real world due to their sensitivity to dynamic operating conditions, such as weather, runway configuration and fluctuating demand. To bypass these challenges and facilitate understanding of capacity-related changes across NAS airports, the FAA typically uses ADR and AAR.

ADRs and AARs are subjective measures to some extent. However, since the facilities consider the impacts any disturbances (e.g. runway construction projects) or new capabilities (e.g. Converging Runway Decision Aid) may have on their ability to handle traffic flows, these empirical rates provide valuable information about changes in airport capacity over time.

Unfortunately, only some of the facilities are required to report called rates and configuration in use across the NAS, and most of them typically do not report on nighttime operations. In fact, MEM is the single airport in the NAS with reportable hours of 00-24, while other facilities' reportable hours usually cover only day-time operations. As a result, impact on called rates during peak periods for SDF and CVG cannot be accurately determined.

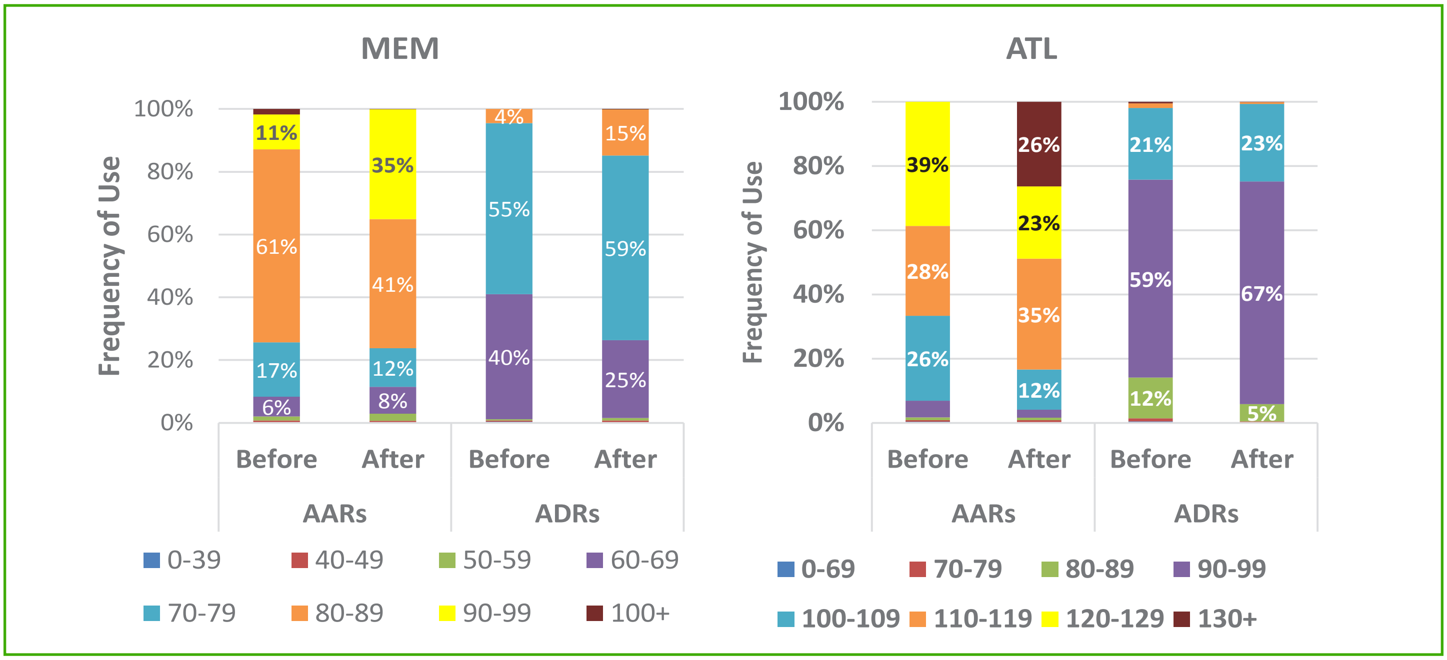


Figure 2 – Facility Reported Called Rates during Peak Periods

Although infrequently used, about one percent of the time, the high-end ADR during peak periods at MEM increased from 80 to 100 departures per hour. More importantly, three months after the implementation of RECAT, MEM started using an ADR of 80 departures per hour about nine percent of the time more often (Figure 2).

The high-end AAR during peak periods at MEM remained at 100 arrivals per hour. However, the use of AARs at or above 90 arrivals per hour become more consistent about three months after implementation, increasing from 13 to 35 percent of the time.

Three months after the implementation of RECAT, MEM consistently used a combined rate of at least 170 operations per hour, which was rarely observed before RECAT.

In May 2014, eight months after RECAT was introduced at SDF, the facility started reporting a new daytime high-end ADR of 58 departures per hour in all meteorological conditions, a 12 percent improvement over the rate of 52 departures per hour that had been typically reported during the previous 10-month period. Two months later, daytime high-end AARs also increased from 52 to 58 arrivals per hour in all meteorological conditions.

Partially delayed by maintenance work on Runway 08L/26R, ATL increased ADR and AAR in mid-October 2014, four months after RECAT deployment. The high-end ADR increased five percent in east flow and four percent in west flow configuration, while the high-end AARs increased five percent in both configurations (Figure 2). During visual meteorological conditions, the facility now uses ADRs of 118 and 108 departures per hour in east and west flows, respectively, and AARs of 132 arrivals per hour in both configurations. Departure rates typically remain at the same level in marginal conditions, while the arrival rates usually reach 110 arrivals per hour, an increase of six percent. During instrument meteorological conditions, ADRs remain lower and at about the same level as in the past, while the AARs remain at the same level as during marginal conditions.

INTER-AIRCRAFT SPACING

Category C and Boeing 757 represent a significant proportion of aircraft – between 60 and 90 percent – during peak periods at MEM, SDF and CVG. Since RECAT separations behind these categories are between 1.0 and 1.5 nautical miles (nm) shorter for most trailing aircraft, average spacing[2] between consecutive departures from, or arrivals to, the same runway decreased during peak periods (Table 3).

Inter-arrival and inter-departure spacing decreased at all four airports. Average inter-arrival spacing is now up to 17 seconds shorter behind Category C and up to 21 seconds shorter behind Boeing 757 aircraft. Average inter-departure spacing is now up to 28 seconds shorter behind Category C and up to 26 seconds shorter behind Boeing 757 aircraft. Distribution of spacing shifted to the left for arrivals and departures, and the modes decreased significantly more than the averages at all four locations, indicating that a majority of aircraft following Category C or Boeing 757 during peak periods are benefiting from the new RECAT separations. Decreased spacing at MEM after introducing RECAT was partially driven by a larger presence of Boeing 757 aircraft

[2] Spacing represents time between wheels-up events for consecutive departures from the same runway, or time between threshold-crossing events for consecutive arrivals to the same runway. We ignored times greater than five minutes because such long spacing cannot be reduced by the new separation standard and would skew the findings.

Table 3 – Spacing Behind Category C and Boeing 757 Aircraft during Peak Hours

Evaluated Metrics by Location		Arrivals				Departures			
		Category C		B757		Category C		B757	
		Before	After	Before	After	Before	After	Before	After
MEM	Proportion of Aircraft (%)	67	65	14	23	68	68	16	26
	Average Spacing (seconds)	159	149	152	143	124	112	125	109
	Spacing Mode (seconds)	139	121	125	112	105	80	99	76
SDF	Proportion of Aircraft (%)	65	67	17	16	75	76	15	15
	Avg. Spacing (seconds)	163	155	148	139	121	110	136	126
	Spacing Mode (seconds)	145	132	126	116	103	85	120	103
CVG	Proportion of Aircraft (%)	75	65	5	9	68	61	4	9
	Avg. Spacing (seconds)	166	150	161	148	141	113	131	128
	Spacing Mode (seconds)	143	118	153	118	120	83	107	93
ATL	Proportion of Aircraft (%)	3	3	13	12	3	3	13	12
	Avg. Spacing (seconds)	151	134	131	110	121	112	121	95
	Spacing Mode (seconds)	135	110	115	85	108	101	112	71

during peak periods. Similarly, about 10 percent of Category C aircraft at CVG was replaced with Boeing 757 and other Category D aircraft during peak periods, resulting in a larger pool of flights that could benefit from reduced separations, and a larger reduction of spacing compared to MEM and SDF.

Spacing behind Category C and Boeing 757 aircraft was smallest at ATL both before and after introducing RECAT, which indicates high airport efficiency. More than 80 percent of arrivals to ATL were classified as Large before RECAT was introduced and trailed Heavies by five nm and Boeing 757s by four nm unless using visual separation. RECAT relaxed both requirements by 1.5 nm, which takes 35 seconds to fly at 150 knots, a representative final approach speed for a Large aircraft. In ATL, the decreases in the mode of 25 to 30 seconds suggest arrivals are taking nearly full advantage of RECAT.

Although most of the ATL fleet consists of previously Large and now Categories D or E aircraft, they are rarely followed by the aircraft with shorter RECAT separations. As a result, spacing behind Categories D and E remained roughly the same as before RECAT deployment.

Table 4 – Average of Daily Peak Quarter-hour Throughput

Airport	Runway	Arrivals		Departures	
		Before	After	Before	After
MEM	18L	7.0	7.7	9.5	11.1
	18R	7.0	7.2	9.5	11.3
	All	**18.7**	**19.6**	**22.3**	**24.9**
SDF	17L	7.1	7.4	8.5	9.7
	17R	6.9	7.0	9.0	10.5
	All	13.6	14.1	16.8	18.5
CVG	27	4.9	5.5	6.7	7.7
	All	**4.9**	**5.5**	**6.7**	**7.7**
ATL	08R	12.0	12.3	18.7	18.5
	09L	10.9	11.2	17.1	17.3
	26L	12.5	12.8	18.7	19.1
	27R	11.2	11.7	15.3	15.9
	All	**31.9**	**32.7**	**36.7**	**34.6**

PEAK THROUGHPUT RATES

Tighter spacing between consecutive flights using the same runway is likely to result in higher throughput during peak periods. To investigate corresponding benefits, we compared daily peak throughput rates for each runway before and after authorization of RECAT separations. Since we wanted to isolate the direct impact of RECAT, we focused on periods with high pressure on runways and evaluated throughput during 15-minute periods[3].

Relative peak runway throughput was consistent with typical fleet mixes. For instance, MEM and SDF have a similar proportion of Category C and Boeing 757 aircraft. However, SDF accommodates significantly more of the Category F and significantly less of the Category D aircraft, resulting in higher throughput rates during peak periods at MEM. On the other hand, CVG has a more varied fleet mix, especially after introduction of RECAT. Compared to MEM and SDF, CVG has a lower proportion of Category C and Boeing 757 aircraft and a higher proportion of Category B, E and F aircraft, resulting in lower runway throughput rates. Finally, Category D and E aircraft dominate operations at ATL, resulting in the least varied fleet mix and separations as well as the least stringent separations. As a result, ATL has the highest runway throughput rates.

Changes in peak runway throughput were commensurate with changes in separations and differences in fleet mix during peak periods. For instance, 73 percent of arrivals to Runway 36L during peak periods at MEM belong to Category C, resulting in a higher throughput benefit compared to Runway 36R with only 57 percent of Category C arrivals. Fleet mix is more consistent across runways at SDF, resulting in less variable throughput improvements.

On average, peak quarter-hour throughput increased by at least one departure and up to one arrival per runway at MEM, SDF and CVG (Table 4).

Increase in peak throughput was more significant at MEM and SDF, where aircraft depart from multiple runways. In addition, the proportion of Boeing 757 aircraft at MEM grew from 17 percent before RECAT to 26 percent afterward, resulting in both more frequent and shorter spacing behind Boeing 757 departures, and an overall throughput benefit of 3.5 additional operations per quarter hour (equivalent to 14 operations per hour).

Direct impact of RECAT on peak throughput at ATL was mixed: an increase of 0.8 arrivals and a decrease of 2.1 departures per quarter hour. This mixed outcome is partially driven by an overall reduction in demand and partially by ATL's typical fleet mix. Although separations behind Category C and Boeing 757 decreased after introduction of RECAT, only 15 percent of traffic is conducted on these aircraft types, while the separations behind most aircraft that operate at ATL remained unchanged (previously classified as Large and now as either Category D or E). As a result, the true magnitude of

[3] Since RECAT has no impact on throughput during periods with light demand, we ignored observations with fewer than eight departures per runway or fewer than 25 departures overall at ATL.

throughput improvement caused by RECAT is overshadowed by fleet mix and demand-related impacts.

However, the lack of a visible throughput improvement for all runways does not imply that ATL did not benefit from the new separations. For instance, Runway 27R at ATL experienced an increase in throughput equivalent to two arrivals and two departures per hour. This observed benefit was most likely driven by traffic spilling over from the now less frequently used offload Runway 28, a remote runway with long taxi times. Therefore, although the actual benefit may be invisible in overall airport throughput rates, it exists elsewhere, such as individual runway throughput rate and corresponding taxi times. This finding clearly illustrates the importance of studying trade-offs between different metrics rather than simply evaluating and blindly reporting their values.

FLIGHT EFFICIENCY IMPACTS

By reducing spacing requirements for many of the aircraft-pair combinations that are typically observed at U.S. airports, RECAT has potential to improve efficiency of terminal and surface flows and operations. During periods of peak demand, reduced inter-aircraft spacing is likely to result in shorter delays that are necessary for safe sequencing and merging, further resulting in shorter queues and taxi-out times for departures, and shorter times in terminal airspace for arrivals.

While RECAT delivered decreased inter-aircraft spacing for the affected categories, this improvement can be observed only if not masked by another operational limitation. For instance, if demand is not high enough or capacity of terminal corner posts is such that it cannot support bringing aircraft closer together on arrival, there will be little opportunity to detect tighter aircraft sequences using empirical data. Similarly, at airports where aircraft have to taxi across active runways, opportunity to take advantage of reduced inter-aircraft spacing will also be limited.

TAXI-OUT AND DEPARTURE QUEUE TIMES

Taxi-out times depend on an airport's layout, runway configuration in use, and operating environment, including demand and meteorological conditions. During periods of peak demand, taxi-out times are often longer because of high pressure on runways and congestion on airport ramps and taxiways.

Because of data gaps, analysis of taxi-out and departure queue times during peak periods at CVG is not possible. On the other hand, MEM, SDF and ATL have an ASDE-X surveillance system and data archive, which can be used to estimate times that each flight spends taxiing between ramp and runway, and waiting in a departure queue. In addition, most operators at ATL report ASQP data for their flights, providing an even richer data set for evaluating flight efficiency at the airport surface (Table 5).

Departure queue times and benefits vary to a smaller extent among runways at the same airport, and to a larger extent across the airports. The two main departure queues at MEM exhibited the greatest decrease in queue times of around 3 minutes, consistent with the corresponding improvements in inter-departure spacing and peak throughput. Average taxi-out times decreased by an additional 0.6 minutes, resulting

Table 5 – Average Departure Queue and Taxi-out Times (Minutes)

Airport	Runway	ASDE-X				ASQP	
		Departure Queue		Spot to Runway		Out to Off	
		Before	After	Before	After	Before	After
MEM	18L	5.9	2.6	13.6	9.7	-	-
	18R	6.0	3.5	13.7	10.6	-	-
	27	2.2	2.1	6.7	6.3	-	-
	All	5.9	3.0	11.5	9.8	-	-
SDF	17L	3.5	2.8	7.9	6.8	-	-
	17R	4.0	3.1	8.0	7.0	-	-
	All	3.8	3.0	8.0	6.9	-	-
CVG	27	-	-	-	-	-	-
	All	-	-	-	-	-	-
ATL	08R	-	-	9.4	9.0	16.7	15.9
	09L	-	-	10.7	9.9	17.7	16.5
	26L	6.4	5.5	11.6	11.2	19.9	18.0
	27R	7.0	6.1	12.4	11.2	20.3	18.3
	All	6.7	5.8	11.2	10.9	18.8	17.6

in three to four minute shorter taxi-out times overall. On the other hand, Runway 27 at MEM is lightly used because of limited queuing space and frequent crossings by departures off runways 18L and 18R. As a result, estimating its queue and taxi-out times and benefits was more complicated and likely not as accurate as for the other two runways at the same airport.

At SDF, the main departure runways exhibited the smallest reductions in average queue times of just under a minute. However, queue times at this location were the shortest as well, thus limiting potential for improvement compared to the other two airports. On average, taxi-out times decreased an additional 0.4 minutes for Runway 17L and 0.1 minutes for Runway 17R, indicating that the most significant portion of flight efficiency improvements at SDF was realized within the queue itself rather than while taxiing.

At ATL, average queue times were about one minute shorter for the two main departure runways in the west flow configuration. Declining demand and more efficient surface flows contributed to this improvement, including less frequent departures of Runway 28. On average, the number of flights that leave their gates within five minutes of another flight taking off from the same runway changed little over the study period, indicating no change in pressure that departing flights apply on runways. Despite the same pressure however, average queue times for ATL's west flow runways decreased by about a minute after RECAT was introduced, clearly indicating improved flight efficiency on the airport surface.

On the other hand, average taxi-out times in ATL improved less than the corresponding queue times when ATL operates in the west flow configuration. In other words, some of the benefit from shorter departure queues is consumed by the less efficient taxiing. A possible explanation may lie in an observed increase of Delta Airlines' share of the traffic at ATL despite an overall demand decrease, and corresponding impacts on typical gate use and ramp service practices. Unfortunately, even though surface data archives for ATL are as rich as they can be, they do not include gate information, which is necessary for further investigation of our hypothesis.

At the three locations where we were able to study changes in taxi-out times, we observed decreased average values after deployment of RECAT separations. Since RECAT deployment and through the end of FY 2014, these savings accumulated to over 86,000 minutes at ATL, while the overall savings during peak periods accumulated to about 148,000 minutes at MEM and 22,000 minutes at SDF.

TIME IN TERMINAL AIRSPACE

The time an aircraft takes to traverse terminal airspace is a function of direction of flight, aircraft performance characteristics, runway configuration in use at the destination airport, and operating conditions, including weather, winds, congestion, protected airspace and terrain. By reducing spacing requirements between many of the consecutive departures or arrivals during periods of peak demand, RECAT is likely to deliver improved flows in terminal airspace and shorter delays due to sequencing and merging.

To avoid ambiguities that may be introduced by the size and shape of different terminal areas, and changes in typical terminal flows since deployment of RECAT, we determined times that arrivals spent within the 40 nm radius around each of the airports, and categorized arrivals by direction of flight and landing runway. Direction of flight, determined as arrivals' crossing point over the 40 nm radius around each of the airports, approximated arrival fixes used for coordination of aircraft transition from en route to TRACON airspace.

For MEM, we compared arrivals during the peak periods between August and October 2012 to arrivals between the same two months in 2013. The 2012 period provided insights into terminal operations before implementation of Area Navigation Standard Terminal Arrival Routes with Optimized Profile Descents (July 2012) and RECAT authorization (November 2012). During the two study periods, most arrivals entered the Memphis Terminal Radar Approach Control (TRACON) in tight clusters around four key directions: Northwest (NW), Northeast (NE), Southwest (SW) and Southeast (SE). During arrival peaks, NW arrivals tended to land on runways 36L and 36R, SW arrivals on Runway 36L, and NE and SE arrivals on runways 36R and 27.

For SDF, we analyzed arrivals during peak periods between August 2010 and October 2014. Most of the arrivals entered the TRACON in tight clusters around five key directions: NW, NE, SW, SE and South. While not evenly distributed, arrivals from each of the five directions landed on runways 35L and 35R.

For CVG, we analyzed arrivals to Runway 09 during peak periods between August 2010 and October 2014, most of which entered the TRACON in tight clusters around five key directions: North, NW, NE, SW and SE.

For ATL, we analyzed all arrivals between August 2010 and October 2014, most of which entered the TRACON in tight clusters around four key directions: NW, NE, SW and SE.

For nearly all arrival-fix runway pairs, average time in terminal airspace decreased after deployment of RECAT separations (Table 6). On average, Atlanta terminal airspace experienced the largest decrease in Time in Terminal Airspace of 38 seconds (4.4 percent), followed by Louisville's 35 seconds (3.8 percent), Cincinnati's 19 seconds (2.4 percent), and Memphis' 14 seconds (1.7 percent). Since RECAT deployment and through the end of FY 2014, these savings accumulated to almost 93,000 minutes at ATL, while the overall savings during peak periods accumulated to about 12,000 minutes at MEM, 8,900 minutes at SDF and 1,200 minutes at CVG.

Table 6 – Average Time in Terminal Airspace for Arrivals (Minutes)

Airport	Arr Fix-Runway	Before		After	
		Arr. Count	Avg. Time	Arr. Count	Avg. Time
MEM	NW-36L	979	16.1	903	15.9
	SW-36L	1,456	13	1,490	12.6
	NW-36R	229	17.7	154	16.6
	NE-36R	1,053	16.5	1,023	16.2
	SE-36R	1,070	13.3	962	13.3
	NE-27	271	12.9	205	12.8
	SE-27	315	12.4	142	12.3
	All	5,373	14.5	4,879	14.2
SDF	NW-35L	7,918	17.9	2,970	16.8
	NE-35L	2,859	18	1,006	17.2
	SW-35L	11,623	16.1	4,538	15.8
	SE-35L	4,159	12.5	1,525	12.4
	S-35L	5,016	13.4	1,548	12.6
	NW-35R	2,594	18.5	1,028	17.9
	NE-35R	5,596	17.1	1,763	16
	SW-35R	2,239	15.7	906	15.6
	SE-35R	11,451	14	3,966	13.2
	S-35R	2,361	13.3	743	12.8
	All	55,816	15.6	19,993	15.0
CVG	N-09	959	14.1	113	13.9
	NW-09	4,037	11	936	11.2
	NE-09	3,697	15.8	682	15.3
	SW-09	6,646	10.9	1,421	11
	SE-09	4,737	14.7	894	14.2
	All	20,076	12.9	4,046	12.6
ATL	NE-08L	180,727	17.4	12,659	16.9
	NW-08L	81,385	12.5	5,892	12.2
	NW-09R	94,848	12.9	10,150	12.5
	SW-09R	78,721	12.1	6,569	11.9
	SE-09R	38,856	15	3,107	14.7
	SW-10	63,961	12.7	6,840	12.4
	SE-10	60,393	16.5	6,325	16.2
	NW-26R	264,866	15.9	24,899	15.1
ATL	NE-26R	158,900	12.5	15,338	11.9
	SW-26R	46,152	17.5	2,463	16.7
	NE-27L	159,802	13.3	18,668	12.8
	SW-27L	84,357	14.7	9,063	14.4
	SE-27L	115,615	12.3	12,152	11.8
	SW-28	105,855	15.4	15,146	15.1
	SE-28	77,906	12.6	9,250	11.9
	All	1,612,344	14.3	158,521	13.7

SUMMARY

Recategorization of wake turbulence categories enabled shorter separations between many of the aircraft-pair combinations that are typically observed at U.S. airports, especially for aircraft belonging to the traditional heavy and Boeing 757 classes. As a result, tighter aircraft sequences are now possible during heavy demand periods and likely to lead to increased capacity and throughput. Consequently, surface and terminal flows during peak periods are more efficient, resulting in shorter runway queues and taxi-times for departures, and less holding and vectoring and shorter times in terminal airspace for arrivals. Increased airport throughput could also result in less frequent use of remote offload runways, which would further improve operator efficiency.

While RECAT delivered decreased inter-aircraft spacing for the affected categories, this improvement can be observed only if not masked by another operational limitation. For instance, if demand is not high enough or capacity of terminal corner posts is such that it cannot support bringing aircraft closer together on arrival, there will be little opportunity to detect tighter aircraft sequences using empirical data. Similarly, at airports where aircraft have to taxi across active runways, opportunity to take advantage of reduced inter-aircraft spacing will also be limited.

Across the first four facilities that were authorized to use RECAT by the end of FY 2014, air traffic controllers took about three to four months to get comfortable with the new aircraft categorization and separations, and start declaring higher airport arrival and departures rates. Although the maximum rates generally increased, they were used infrequently. However, the high-end range of ADRs and AARs has been used more frequently compared to before RECAT, indicating that the controllers can now sustain high-pressure workload for longer periods of time.

Spacing behind Category C and Boeing 757 aircraft is shorter for both arrivals and departures during peak periods. Interestingly, at all four locations, spacing modes decreased significantly more than their averages, indicating that the majority of aircraft following Category C or Boeing 757 during peak periods are benefiting from the new RECAT separations.

On average, peak quarter-hour throughput increased by at least one departure and up to one arrival per runway at MEM, SDF and CVG, the three airports with a high proportion of Category C and Boeing 757 aircraft. Partially caused by a significant growth of Boeing 757 fleet, MEM experienced the highest increase in peak throughput, equivalent to 13 additional operations per hour.

At ATL, on the other hand, we observed an increase of 0.8 arrivals and a decrease of 2.1 departures per quarter hour. This mixed outcome is partially driven by an overall reduction in demand and partially by ATL's fleet being dominated by the aircraft less affected by RECAT. However, Runway 27R at ATL experienced an increase in throughput equivalent to two arrivals and two departures per hour, an improvement that was most likely driven by both RECAT and the traffic spilling over from the now less frequently used offload Runway 28.

Departure queue delays decreased across the three locations with ASDE-X surveillance: around 3 minutes at MEM, and just under a minute at SDF and ATL. Average taxi-out times decreased as well, resulting in overall taxi-out time savings between 1.2 and 4.6 minutes. Since RECAT deployment and through the end of FY 2014, these savings accumulated to over 86,000 minutes at ATL, while the overall savings during peak periods accumulated to about 148,000 minutes at MEM and 22,000 minutes at SDF.

For nearly all arrival-fix runway pairs, average time in terminal airspace decreased after deployment of RECAT separations. Since RECAT deployment and through the end of FY 2014, these savings accumulated to almost 93,000 minutes at ATL, while the overall savings during peak periods accumulated to about 12,000 minutes at MEM, 8,900 minutes at SDF and 1,200 minutes at CVG.

LOWER VISIBILITY MINIMA FOR INSTRUMENT APPROACH PROCEDURES

Precision approach and landing operations require ground and airborne equipment of sufficient performance capability. Ranked as Category I, II or III, Instrument Approach Procedures (IAP) with vertical guidance require progressively more capable avionics and ground infrastructure but enable safe approaches during progressively worse visibility conditions.

During the last few decades, numerous airports across the National Airspace System (NAS) improved their runway guidance and lighting systems. Operators also have invested in several cockpit technologies that enhance pilot awareness of their surroundings near or on the surface. For example, Head-Up Displays (HUD) provide flight and navigation information on a clear panel that pilots can review while looking out the window. With this more integrated view in a single field of vision, pilots now can execute safe precision approaches during some of the low-visibility conditions that used to halt landings.

Prior to publishing Order 8400.13[1] "Procedures for the Evaluation and Approval of Facilities for Special Authorization Category (CAT) I Operations and All CAT II and III Operations," the FAA required at least 2,400 feet visibility along runways without touchdown zone or runway centerline lighting for Category I approaches. In October 1997, the agency relaxed the Runway Visual Range (RVR) minima requirement to 1,800 feet when an autopilot (AP), flight director (FD) or HUD is used to the Decision Altitude (DA) (Figure 1). Since then, the FAA continued to leverage improved airborne capabilities, and updated the Order and requirements concerning instrument landing systems (ILSs), approach and runway lighting, RVR sensors, cockpit technologies, and aircraft and aircrew certification, including:

- Special Authorization (SA) CAT II Operations: Order 8400.13B, dated February 2005, authorized publication of procedures for Category II approaches with RVR minima down to 1,200 feet and Decision Heights (DHs) down to 100 feet for runways without touchdown zone or runway centerline lighting. Such procedures may be flown by specially authorized flight crews operating aircraft certified for Category III operations and using a HUD to touchdown (TD). Before this update, only Category I approaches were possible to such runways, which required ceilings of at least 200 feet and RVR of at least 1,800 feet.
- SA CAT I Operations: Order 8400.13D, dated October 2009, authorized publication of procedures for Category I approaches with a DH down to 150 feet and visibility minima down to 1,400 feet for runways without touchdown zone or runway centerline lighting. Such procedures may be flown only by specially authorized flight crews operating aircraft certified for Category II or III operations. Prior to this update, Category I approaches to these runways were possible only when ceilings were at least 200 feet and visibility was at least 1,800 feet.
- CAT II RVR 1000 Approach Operations: Order 8400.13D, dated October 2009, relaxed the RVR minima requirement for standard Category II approaches to 1,000 feet when HUD is used to touchdown. Ground and airborne equipment requirements for standard Category II operations remained the same as under the previous version of the Order.

Lowering IAP minima requirements improves access to runways during periods with low-visibility conditions, and in some cases, it enables access during the same conditions when no landings were possible in the past. The key benefits include avoiding the costs of necessary responses and operational impacts during such conditions.

[1] The most recent version of Order 8400.13 can be found at http://fsims.faa.gov/wdocs/orders/8400_13.htm.

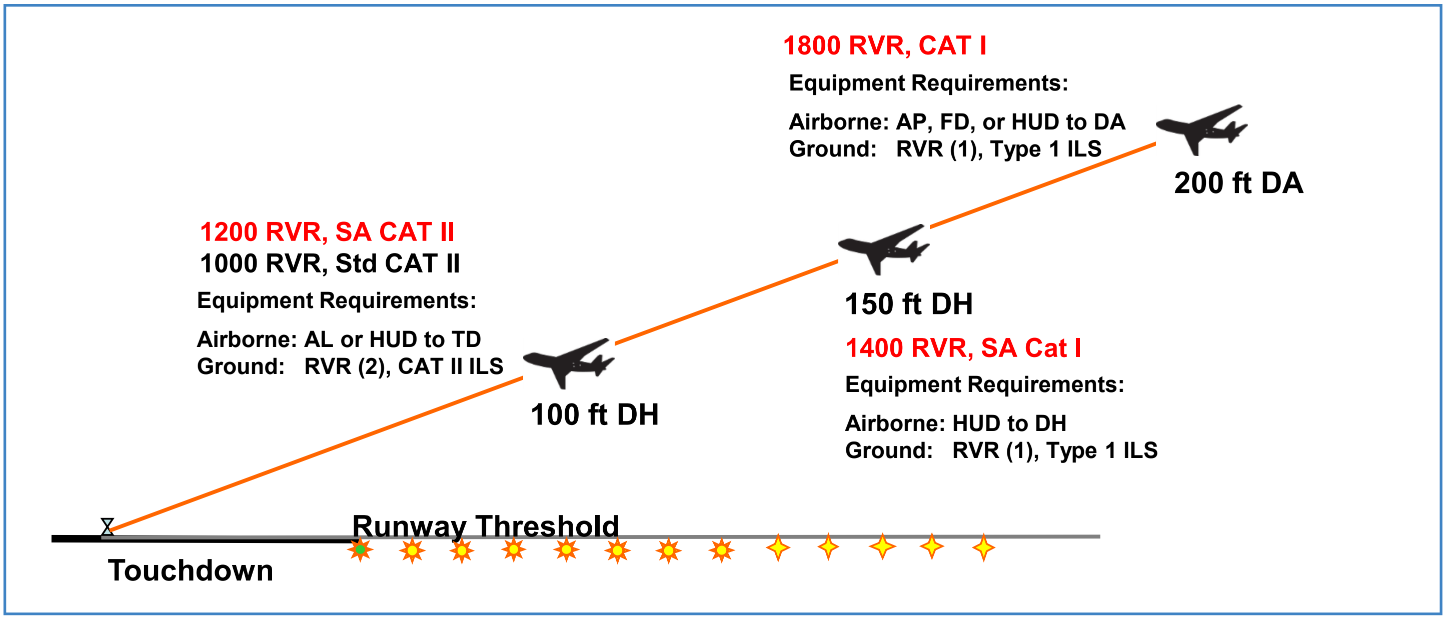


Figure 1 – Requirements for SA CAT I, SA CAT II and Standard CAT II RVR 1000 Operations

For instance, significant loss of airport capacity during low-visibility periods results in less efficient terminal flows and delays due to holding and vectoring. Disruptive changes in runway configuration that facilitate use of IAPs with lower minima requirements may be necessary, assuming surface winds allow it. Traffic management initiatives like ground delay programs or ground stops may be necessary as well, resulting in additional delays and sometimes even costly cancellations.

METHODOLOGY AND FINDINGS

Because of inconsistent archiving of relevant details across the NAS, it's impossible to recreate a history of exactly what may have been changed in IAP requirements and when it happened. Although available as far back as 2000, location-specific RVR data is incomplete as well. Recent records in both sets are more accurate and complete, so the FAA's NextGen office focused on changes that have been implemented since 2011 and affected SA CAT I, SA CAT II or standard CAT II RVR 1000 operations, and investigated resulting impacts on airport throughput.

Since low-visibility conditions and significant demand rarely occur at many of the airports across the NAS, we were unable to investigate gradual improvements in airport access after each individual reduction in required visibility minima was authorized. Instead, we compared airport access during affected periods with low visibility after the most recent update in IAP specifications to the access before the original authorization of SA CAT I, SA CAT II, or standard CAT II RVR 1000 operations.

The first step of our analysis included cross-referencing historical data for required visibility minima, visibility conditions and arrival operations from calendar years 2011-2014. Each of the three data sources presented its own challenges and limitations elaborated below.

VISIBILITY MINIMA REQUIREMENTS

The digital archive of terminal procedures contains historical IAP specifications, including required DH and RVR minima. We investigated new IAP publications and changes in IAP specifications over time, and found 167 changes in visibility minima requirements that applied to 111 runways at 59 airports and published on 36 different dates between January 2011 and January 2015.

In 101 of the 167 cases, changes in required minima enabled SA CAT I operations, with about three-fourths of the changes applicable to runways that already supported CAT II or CAT III operations. SA CAT I operations were authorized at 55 airports[2] and SA CAT II operations at 20 airports. Standard CAT II RVR 1000 operations were authorized at four runways that already supported CAT II operations and at 20 runways that supported Category III operations; each of these runways already supported CAT I operations.

LOW-VISIBILITY EVENTS

RVR represents the horizontal distance a pilot can see down the runway from the approach end. RVR is determined by an RVR system[3] which uses electronic sensors to measure visibility, background luminance and runway light intensity, and ascertain the distance a pilot should be able to see down the runway. The system is required for precision landing and takeoff operations in the NAS.

Although RVR can greatly vary from one runway to another at the same airport, data recorded by the Automated Surface

[2] At 23 of the 55 airports, changes in required visibility minima affected only SA CAT I operations.

[3] For more information, please visit the FAA's website: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops

Observing System[4](ASOS), and archived by the National Climatic Data Center (NCDC) consists of a single value for the whole airport. Typically determined by using the touchdown zone sensor on the primary arrival runway, RVR data is updated every minute regardless of visibility and is available beginning in 2000. The data is incomplete, but fortunately for most airports that were authorized to use SA CAT I, SA CAT II or standard CAT II RVR 1000 operations between 2011 and 2014, ASOS RVR records were available for more than 80 percent of the time. Only three of the airports had a coverage of less than 10 percent of time: Charleston Air Force Base/ International Airport (CHS), Syracuse Hancock International Airport (SYR), and Salt Lake City International Airport (SLC). Therefore, resulting performance impacts were impossible to accurately determine from these airports, and their inclusion did not strongly influence our results.

RVR data was available for 47 of the 59 airports with changes in required minima between 2011 and 2014. At most of these airports, RVR of up to 1,800 feet is rare, with only nine of the 47 airports experiencing such conditions for more than 0.5 percent of the time, and 34 of the airports for less than 0.1 percent of the time (Figure 2).

Geographic features predispose some of these airports to low-visibility conditions. For instance, Seattle-Tacoma International Airport (SEA), Snohomish County Airport (PAE), Bellingham International Airport (BLI), and Portland International Airport (PDX) are coastal airports in the Pacific Northwest with mountains to their east and frequent occurrences of dense fog. Spokane International Airport (GEG), Sacramento Executive Airport (SMF), and Fresno Yosemite International Airport (FAT) are located in West Coast valleys, which are prone to the formation of early morning fog.

RVR values can considerably differ from one runway to another at the same airport as well as considerably fluctuate over short periods of time at the same location. Archived data, on the other hand, includes one minute updates for the whole airport. As a result, subtle variations in visibility that may have impacted operational decisions made by pilots, air traffic controllers and airport operators are impossible to accurately understand. Therefore, resulting access-related impacts can only be investigated for the whole airport as opposed to by runway, and across the range of precision approaches and landing categories as opposed to by category.

Although recent changes in Order 8400.13D apply to periods with RVR of less than 1,800 feet, we introduced a 200-foot threshold to account for subtle variations in RVR around an airport, and focused on occurrences of RVR of less than 2,000 feet that lasted 10 minutes or longer. In addition, if time between two adjacent occurrences was shorter than 10 percent of their duration, we assumed that the system was unable to take advantage of such temporarily improved conditions, and considered the two occurrences and time in-between as a single low-visibility event. In the end, we found

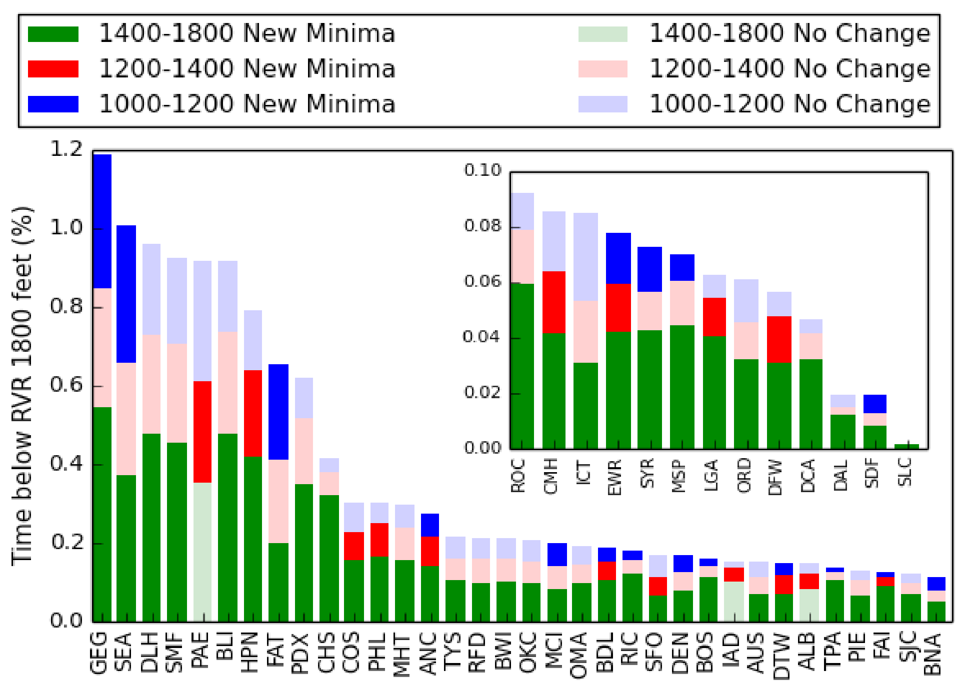


Figure 2 – Occurrence of Low Visibility by Airport with Changes in Minima Required for Precision Approaches

[4] For more information, please visit NOAA's website: http://www.nws.noaa.gov/asos/vsby.htm

2,774 low-visibility events between 2011 and 2014 at the 47 airports included in our study.

AIRPORT ACCESS

Timing and duration of low-visibility occurrences are only two of the key factors determining the magnitude of resulting impacts on airport access. Demand for airport services during the same periods is another one. To account for these key factors, we compared airport access during each low-visibility event to the average access observed during nearby-like periods. For a low-visibility event, nearby-like periods are the periods of the same duration that occurred on the same day of the week and same time of the day during five weeks before and after the event. Only 1,228 of the previously identified 2,774 low-visibility events contained sufficient demand during nearby-like periods to warrant further investigation[5].

We used surveillance data and MITRE Corporation's Threaded Track[6] tool to determine aircraft landing times and runways during periods with low and nearby-like periods. Then we computed ratios between arrival throughput during each low-visibility event and the average arrival throughput during its nearby-like periods, representing relative access, or a proportion of flights that gained access to the airport despite the low-visibility conditions. Finally, to investigate impacts of changes in RVR minima requirements, we analyzed differences in such Relative Access before and after the requirements were authorized using Normalized Frequency, or the distribution of Relative Access normalized by the number of low-visibility events. Since the occurrence of low-visibility events can greatly differ over time, the normalization facilitates comparison of distributions by assuring that the areas under the curves before and after study periods are equal.

In most cases, Relative Access during periods with low visibility is less than one (Figure 3). In many instances, Relative Access is equal to zero, indicating no landings were accomplished at all. At times, Relative Access will exceed 1.0; a low-visibility event's throughput can exceed the average of its nearby-like periods when throughput is light and the low-visibility event was not severe.

Unfortunately, we were unable to investigate differences in Relative Access before and after RVR minima requirements were changed at individual sites because the number of events for any one airport was too small to draw meaningful conclusions. Instead, we aggregated low-visibility events across airports and determined that relative arrival counts did improve after reduction of RVR minima requirements.

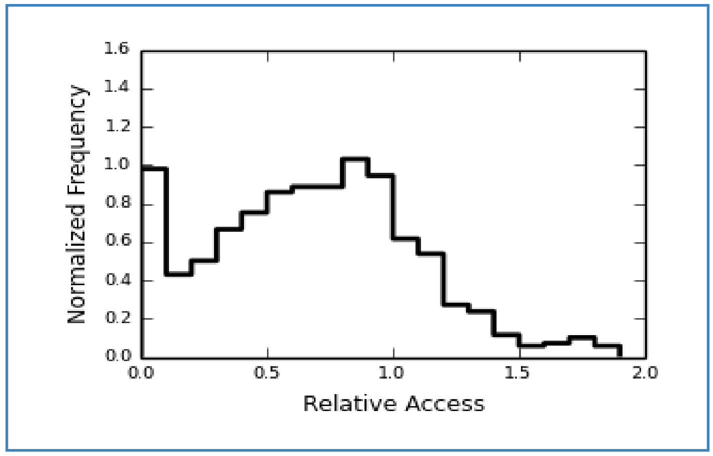


Figure 3 - Relative Arrival Access during Low-Visibility Events

Frequency of no access has been roughly cut in half after reduction of RVR minima requirements across the NAS. Relative access improved as well: the distribution of Relative Access shifted to the right, indicating a higher proportion of flights is now able to land during the same low-visibility conditions. On average, 72 percent of flights that typically request access to an airport can now land during low-visibility periods as well, which is an additional 17 percent of flights compared to before authorizing reduction in RVR minima requirements[7]. (Figure 4).

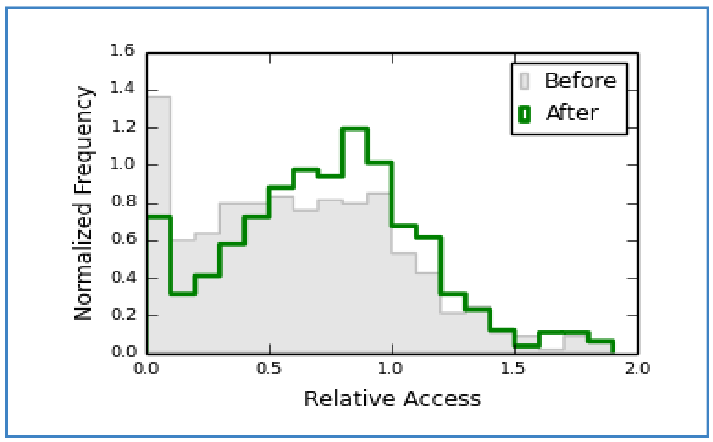


Figure 4 – Relative Access Before and After Minima Changes

This improvement was driven mainly by enabling additional SA CAT I operations. About half of the low-visibility events occurred at airports affected only by this type of minima reduction, with the average Relative Access during low-visibility periods increasing to 75 percent of flights that typically request access to these airports (Figure 5a). For other airports, the change in Relative Access was insignificant (Figure 5b).

[5] We excluded low-visibility events for which the median of the arrival counts for the like-periods was fewer than three; comparison of such low counts is not meaningful because variation in counts is as large as the counts.

[6] Threaded Track is a fusion of data from the National Offload Program, Airport Surface Detection Equipment-Model X (ASDE-X), and the Traffic Flow Man agement System message set.

[7] Prior to authorizing reduction in RVR minima requirements, 55 percent of flights that typically request access to an airport was able to land during low visibility periods.

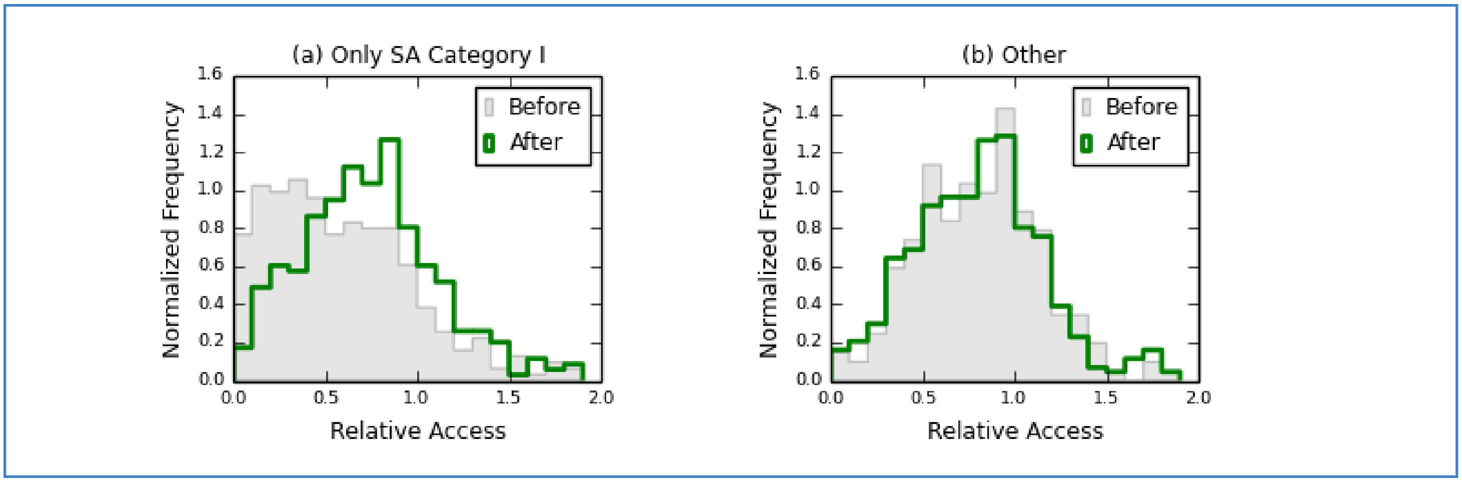


Figure 5a-b – Relative Access for Airports with Expanded Use of SA CAT I and CAT II Operations

PERIODS WITH NO AIRPORT ACCESS

At some point, an airport will stop accepting arrivals during periods with low visibility, usually because RVR falls below the required minima for the runways in use. Sometimes an airport may stop accepting arrivals even if the minima are not exceeded, usually because it is too difficult for controllers to identify flights that are capable of precision approaches with lower minima requirements.

Frequency of no access across the low-visibility events has been cut roughly in half after reduction of RVR minima requirements across the NAS, from 12 percent to 6.4 percent of the time. We also investigated changes in duration of periods with no access and focused on the proportion of time with extended periods of no access during low-visibility events. First, we analyzed the duration of intervals with no access during like-periods. We selected the 99th percentile to represent extremely long intervals with no access, or extreme gaps, during normal conditions. Then we investigated the duration of intervals with no airport access during low-visibility events and found that the extreme gaps are on average 12.4 percent longer during low-visibility events (Figure 6). In addition, compared to before, the average duration of extreme gaps decreased from 40 to 26 percent of the overall duration of the low-visibility events after authorization of reduced RVR minima requirements for CAT I and CAT II operations (Figure 7).

The decrease in the average duration of extreme gaps was less substantial at airports with reduced minima requirements for SA CAT I operations (from 36 to 27 percent of the overall duration of the low-visibility events), and more substantial at airports with changes that expanded the use of CAT II operations (from 45 to 25 percent). This finding suggests that facilitating SA CAT II operations results in a more significant improvement by enabling airport access during periods when none was available in the past. This is unsurprising because 75 percent of all changes in minima providing for expanded use of SA CAT I operations were implemented for runways that already supported precision approaches during periods with RVR below 1,800 feet.

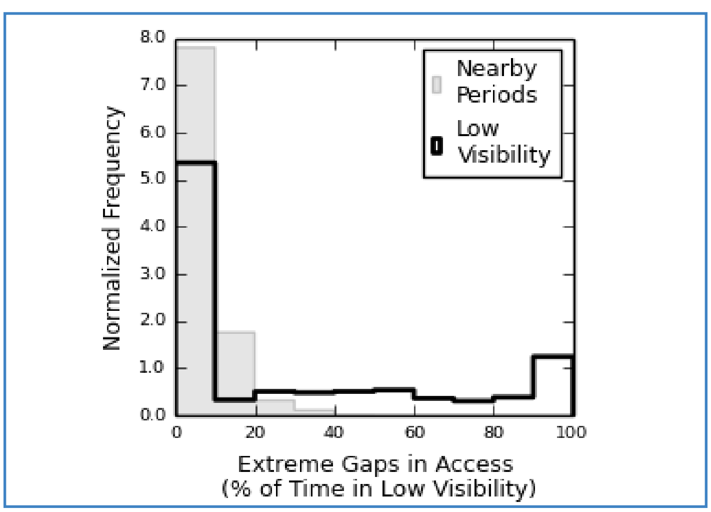


Figure 6 - Times in Extreme Gaps for Low Visibility Events and Nearby Periods

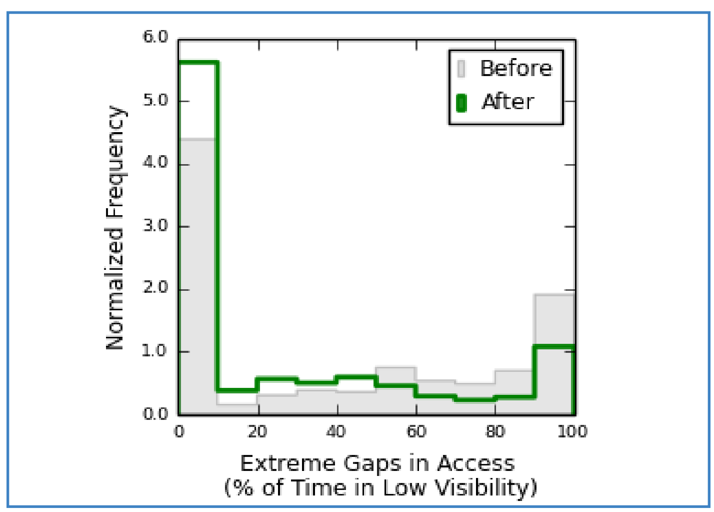


Figure 7 - Times in Extreme Gaps Before and After Minima Changes

SUMMARY

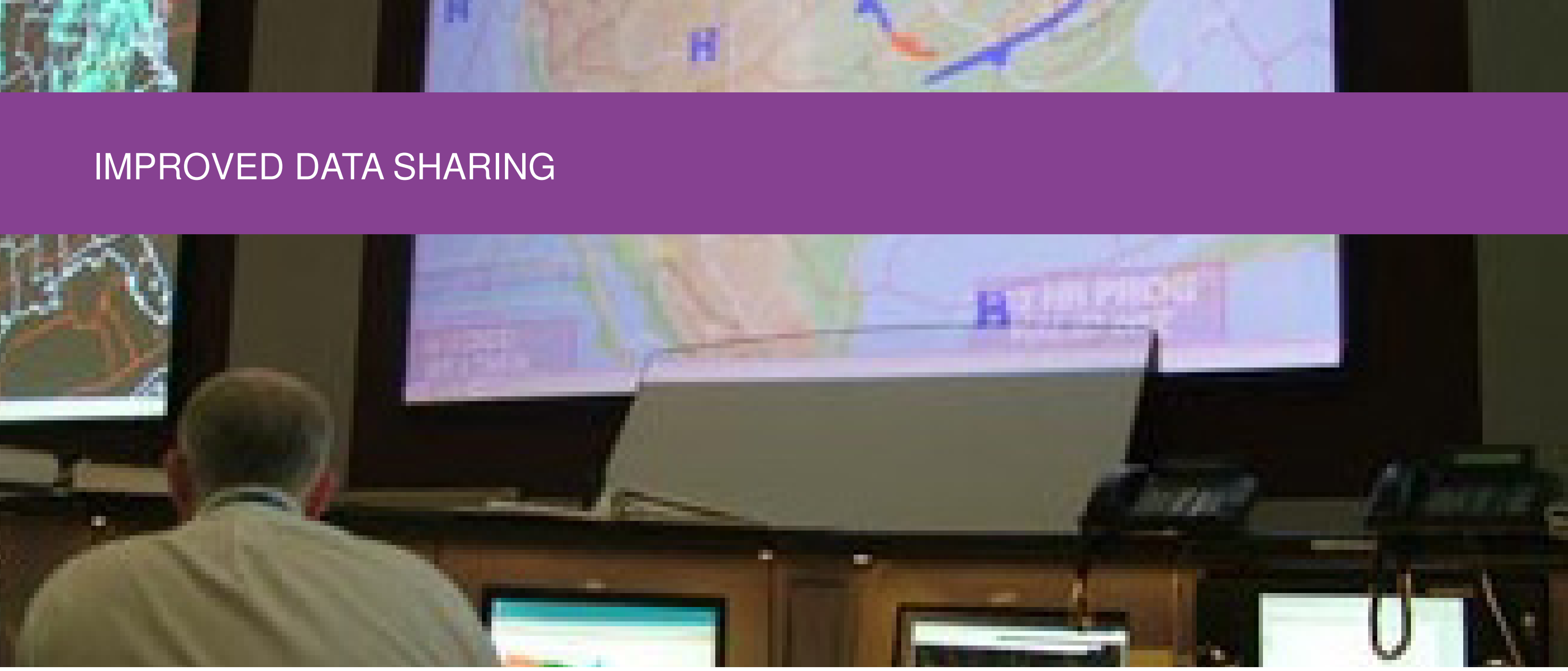
Over the last few decades, numerous airports across the NAS improved their runway guidance and lighting systems. Operators also have invested in several cockpit technologies that enhance pilot awareness of their surroundings near or on the surface. Head-Up Displays (HUD), for example, provide flight and navigation information on a clear panel that pilots can review while looking out the window. With this more integrated view in a single field of vision, pilots now can execute safe precision approaches during some of the low-visibility conditions that previously halted landings.

Prior to publishing Order 8400.13, the FAA required at least 2,400 feet visibility along runways without touchdown zone or runway centerline lighting for Category I approaches. In October 1997, the agency relaxed the RVR minima requirement to 1,800 feet when an autopilot, flight director or HUD are used to DA. Since then, the FAA continued to leverage improved airborne capabilities. The agency updated the Order and requirements concerning ILSs, approach and runway lighting, RVR sensors, cockpit technologies, and aircraft and aircrew certification. These provide for publication of procedures for Category II approaches with RVR minima of 1,000 feet and DH of 100 feet, and approaches with RVR of 1,400 feet and DH of 150 feet.

Our study focused on access-related impacts at the 47 airports for which we were able to obtain consistent records documenting changes in procedure minima requirements and RVR conditions over time. Access-related impacts are influenced by the timing and duration of low-visibility occurrences and by the demand for airport services during the same periods. To account for these key factors, we compared airport access during each low-visibility event to the average access observed during nearby-like periods. For a low-visibility event, nearby-like periods are the periods of the same duration that occurred on the same day of the week and same time of the day during five weeks before and after the event.

After reduction of RVR minima requirements across the 47 airports included in our study, frequency of no access during periods with RVR below 1,800 feet was cut almost in half, from 12 percent to 6.4 percent of the time. In addition, extended periods with no access during low-visibility events are now shorter too, decreasing on average from 40 to 26 percent of the overall duration of the low-visibility events. Most importantly, an additional 17 percent of flights that typically request access to an airport now can land during low-visibility periods.

Although these benefits were mostly spread across airports supporting SA CAT I operations, our study confirmed that facilitating SA CAT II operations results in a more significant benefit by enabling airport access during periods when none was available in the past.



IMPROVED DATA SHARING

Users of the National Airspace System (NAS) rely on many types of information provided by the FAA. Some of that information is static and available via products with regular publication cycles, such as aeronautical charts. However, the FAA also is sharing more real-time data, including surveillance data, information about traffic flow management initiatives, weather observations and forecasts, and real-time aeronautical information, such as Notices to Airmen (NOTAMs) and the status of Special Use Airspace (SUA). The FAA traditionally shared such information using a variety of technologies, including the radio, telephone, Internet, and dedicated connections. However, in recent years, the FAA leveraged new information management paradigms to improve the way in which it shares dynamic NAS data with external users. This chapter describes how these initiatives are making more data accessible at a lower total cost, and how this data is impacting NAS users.

Improved delivery typically results in lower costs, while improved content should enable operational benefits. The operational impacts of these improvements depend on the particular information needs of users. Improved outcomes arrive only when better information content and delivery are used to influence decisions. In practice, benefits of improved information-sharing can be difficult to measure because flight operators integrate information from many sources as they make decisions and plans.

For this initial assessment, the FAA's NextGen Office relied on interviews with data consumers to try to determine how this information is being used, and what, if any, are the benefits. We asked several stakeholders about their experiences. Some were airline personnel responsible for ramp operations, flight dispatch or overall system control. Others were airport managers who use such data to improve efficiency of their gate and surface operations. Still others were companies that provide value-added services to these NAS users, helping them to access, integrate and assimilate real-time data to meet their operational needs[1][1].

OVERVIEW OF DATA DISTRIBUTION VIA SWIM

System Wide Information Management, or SWIM, is one of the FAA's transformational NextGen programs. The goal of SWIM is to transition from direct connections to a publish-subscribe model. Such a model is known as a Service Oriented Architecture or SOA. SWIM is replacing unique system interfaces with a single point of connection for each user to receive multiple data products. For existing data sets, such as Airport Surface Detection Equipment-Model X (ASDE-X) surface movements or traffic flow management flight tracking, SOA provides a more efficient and cost-effective alternative to establishing a multiplicity of direct connections. This improved distribution system also is facilitating the publication of new information, such as Time Based Flow Management (TBFM) metering times and digital NOTAMs.

The data being provided via SWIM falls into one of three categories. First is flight and flow information, which consists of data on aircraft position and flight status. Next is aeronautical information, which can be either static or dynamic. This data is typically used for pre-flight planning, but also can be used for the safe flight of the aircraft. Examples include digital NOTAMs, airport reference and configuration data, and the status of Special Activity Airspace (SAA). The third category is up-to-date weather observations and forecasts.

Table 1 on page 42 highlights the different types of available data products with a brief description of each. This table will serve as a guide for the remainder of this chapter.

[1] The number of actual end-users far exceeds the number of subscribers to SWIM since many of these subscribers are third-party vendors who build value-added applications using this data.

Table 1 – Different Types of Data Products Available via SWIM

Data	Producer	Description
FLIGHT / FLOW	TFMS	Traffic Flow Management System (TFMS) provides Aircraft Situation Display to Industry (ASDI) data, including aircraft scheduling, routing and positional information.
	TBFM	Time Based Flow Management (TBFM) provides a variety of aircraft metering information, airport configuration and adaptation data.
	STDDS	SWIM Terminal Data Distribution System (STDDS) provides surface movement data (ASDE-X), Runway Visual Range (RVR) and a variety of departure event data.
	SFDPS	SWIM Flight Data Publication Service (SFDPS) provides a variety of en route flight data, such as flight plans, beacon codes and handoff status. SFDPS also disseminates data regarding airspace, such as sector configuration, route status, Special Activity Airspace (SAA) status and altimeter settings.
AERONAUTICAL	AIM	The Aeronautical Information Manual (AIM) provides airport reference and configuration data, including definitions and schedule information for SAA, Temporary Flight Restriction (TFR), procedure (Area Navigation/Required Navigation Performance) data and obstacles. AIM also provides Notices to Airmen (NOTAMs).
WEATHER	ITWS	Integrated Terminal Weather System (ITWS) provides a variety of weather information in graphic and textual forms, such as windshear and microburst predictions, storm cell and lightning information, and terminal area winds aloft.
	WMSCR	The Weather Message Switching Center Replacement system (WMSCR) collects, processes, stores and disseminates textual aviation weather products such as pilot reports (PIREPs) and altimeter settings.
	WARP/EWD	Weather and Radar Processor (WARP) provides Next Generation Weather Radar (NEXRAD) data.

SWIM BASICS

SWIM includes standards, infrastructure and governance that enable information exchange between NAS entities and their stakeholders, both inside and outside of the FAA. Its SOA simplifies the building of interfaces to existing systems, and ensures that new systems and applications can be created and integrated more quickly. SWIM can be thought of as a multi-layered framework illustrated in Figure 1 on page 44, consisting of application end systems, standards for data exchange, and a NAS Enterprise Messaging System (NEMS), all of which run on the FAA's secure Internet Protocol (IP) network.

EXTERNAL SWIM CONNECTION

In order to maintain the security of the NAS systems that are providing the data, all external users must connect to the FAA's network via one of four secure entry points, known as NAS Enterprise Security Gateways (NESG). The process of establishing and verifying a new external user's connection to the NESG is part of what is known as the "on-ramping" process. Another important part of on-ramping consists of working with users to test the security of their individual connections to each new data service, and to ensure that they are able to correctly parse and interpret the data. In order to do this, users are first connected to an R&D domain for basic testing in a protected environment. This is followed by a brief transition to the FAA's NAS Test Bed (FNTB) for interoperability testing before switching to a live data connection.

The current on-ramping process for new external users can last up to six months, but the SWIM program hopes to reduce that to two months through a combination of consumer outreach and internal process improvement. Table 2 on page 43 summarizes the number of on-ramping and live subscriptions. The number of live subscriptions should significantly increase as on-ramping consumers transition to live subscription.

As illustrated in Figure 2 on page 44, the largest numbers of external consumers are those who are switching over from the legacy ASDI feed to TFMS, or from the legacy ASDE-X feed to STDDS.

Table 2 – The Number of On-ramping and Live Subscriptions to SWIM Products

	Producer	Service	Date Available	On-ramping Subscriptions	Live Subscriptions
FLIGHT/FLOW DATA	TFMS	TFM Data Cat 3/4/5	2015	182	8
		TFM Data Cat 1/2	2015	-	-
		TFMS Flight - Legacy ASDI	2015	1	-
	TBFM	TBFM Metering Publication	2014	11	1
	STDDS	Surface Movement Event (SMES)	2014	70	17
		Airport Data (APDS)	2015	59	5
		Tower Departure Event (TDES)	2015	6	-
		Status Service (ISMC)	2015	-	-
		Terminal Automation Information Service (TAIS)	2015	4	-
	SFDPS	En Route Flight Data Publication (ERFDP)	2015	3	-
		En Route Airspace Data Publication (ERADP)	-	1	-
		En Route Operational Data Publication (ERODP)	-	-	-
		En Route General Message Publication (ERGMP)	-	-	-
		SFDPS (All)	-	27	-
AERONAUTICAL DATA	AIM	FNS NOTAM Distribution	2014	41	1
		AIM SAA	2014	2	-
		Get Static SAA	2014	-	-
		Put Static SAA	2014	-	-
		SAA Operational Status	2014	-	-
		SAA Schedule Notification	2014	-	-
		Static SAA Update Notification	2014	-	-
		AIM (All)	2014	4	-
WEATHER DATA	ITWS	ITWS Publication	2014	41	6
	WARP/EWD	WARP Publication	2015	-	-
		NWS WINS WCS	-	-	-
		NWS WINS WFS	-	-	-
		WARP/EWD (All)	-	3	-
	WMSCR	Publish Pilot Report (PIREP)	2015	-	-
		Publish Alt Set	-	-	-
		Submit PIREP	-	1	-
		Submit Alt Set	-	-	-
		ACK Weather Report	-	-	-
		Report Retrieval Service	-	-	-
		WMSCR (All)	-	4	-

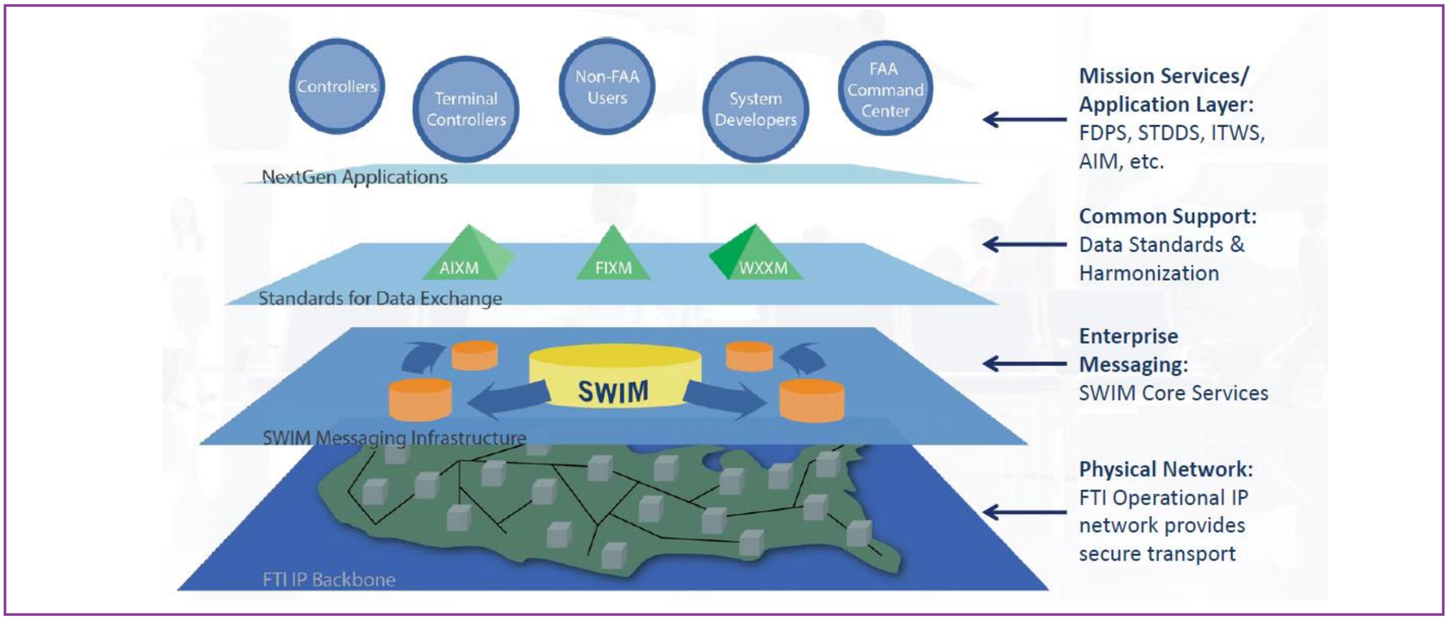


Figure 1 – Multi-Layered Framework of SWIM

OPERATIONAL AND PERFORMANCE IMPACTS

BENEFITS TO FLIGHT OPERATORS

Our interviews revealed benefits to flight operators arising from all of these improvements to data content, especially from the availability of surface traffic surveillance data. Most of these benefits come from enhanced awareness about individual flights and the situation at particular airports. Airlines and vendors worked to merge FAA-provided data with information from other systems to provide more comprehensive and integrated pictures to various operational positions. In some cases, software also uses the data to provide alerts or to improve predictions about aircraft movements.

The following sections describe benefits to flight operators by user role, with a summary presented in Table 3 on page 45.

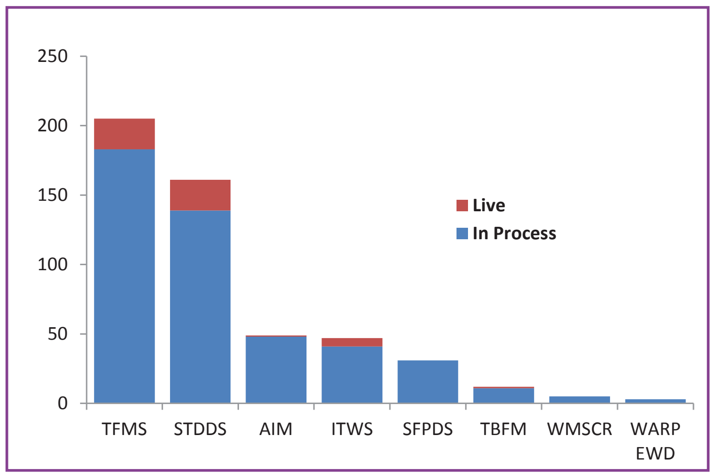


Figure 2 – Number of SWIM Applications by Stage and Producer as of July 1, 2015

RAMP CONTROL

Ramp controllers are perhaps the most obvious beneficiaries of surface traffic surveillance data. These controllers are responsible for the safe and efficient flow of traffic on an airport's non-movement area, the part of the surface beyond the purview of air traffic control, which is generally between taxiways and gates. Most large airports have several ramp areas, and an airport may have one or several ramp towers to house ramp controllers. Many ramp towers are operated by the airport on behalf of all flight operators using the corresponding ramp areas. In other cases, where a ramp area's gates are mainly for a single carrier, the tower may be operated by that carrier.

As ramp controllers choreograph the movement of aircraft contending for access to gates, pavement, and deicing pads, they maintain a constantly evolving mental picture of where aircraft are, need to go, and will be. Some of this picture is drawn from visual inspection of the ramp areas through windows or via video feeds. Some is drawn from information systems that display details about flight plans and status. Still more comes from radio and telephone communications with gate agents, the airline's operations center, pilots, airport operators and air traffic control (ATC). The recent addition of ASDE-X traffic surveillance data to this set of tools, and its integration with existing information systems and displays, has improved the completeness and precision of this picture for ramp controllers.

One benefit of this better picture is that tactical decisions about movement have more efficient outcomes. One interviewee described a common situation in which the taxi

Table 3 – Summary of the Benefits to Flight Operators

User Role	Operational / Performance Impact	Data Sets Used
Ramp control	Gate management • By knowing more precisely when an arriving flight is expected at a gate, ramp controllers report improved gate use with fewer arrivals stuck waiting for a gate.	• STTDS surface movement data • TFMS airborne traffic data
	Surface traffic management • With better information about queue lengths for de-icing or departure, ramp controllers can manage pushback from the gate in order to minimize time on the tarmac. • In low-visibility conditions, ramp controllers report that surface surveillance data has proven invaluable for managing surface traffic.	• STTDS surface movement data
Operations control	Reducing excessive departure delays • By monitoring real-time airborne and surface delays, operations managers can make better decisions about prioritizing departures, thereby avoiding crew timeouts or violations of the tarmac delay rule.	• STTDS surface movement data • TFMS airborne traffic data
Dispatch	Flight following and support • Information on SUA status and other NAS status is used to help pilots select their preferred route of flight. • Using information on RVR at the destination airport, dispatchers inform pilots of local conditions and advise them of preferred arrival and approach procedures.	• AIM SUA status and digital NOTAMs • STDDS RVR data
Gate/ground management	Resource management • By knowing more precisely when flights are arriving, gate agents and ground crews can be deployed with less wasted time.	• STTDS surface movement data • TFMS airborne traffic data
Planning and analysis	Post-event review and process improvement • Operations analysts report that archived surveillance data is a useful tool for identifying problems and inefficiencies, and for defining solutions.	• STTDS surface movement data • TFMS airborne traffic data

lanes or "alleys" around the gate area are too narrow to allow aircraft to pass in opposite directions. The awareness afforded by ASDE-X data that an arrival is about to enter the ramp area may avoid unnecessarily delaying that arrival. A departure that might otherwise block the alley could be delayed instead. Better awareness of the taxiway situation can also help ramp controllers avoid congestion, especially during irregular operations.

A recurring theme in our interviews was that better surveillance information was especially valuable in irregular situations. For ramp controllers, very low visibility, snow removal and aircraft de-icing are three common examples. In low visibility, with the absence of visual cues for pilots and ATC, airport operations are slower and less predictable. Surveillance data in ramp towers lets ramp controllers understand the status of their flights without exacerbating pilot and ATC workload via radio and phone calls. Where ground vehicles are included in surveillance data, ramp controllers have much more precise information about the timing of snow removal on runways and taxiways and their subsequent availability. When de-icing is necessary, ramp controllers use surveillance data to monitor the availability of de-icing pads and queues.

The availability of surface surveillance data is one reason for the increasing use of departure queue management by carriers. Rather than allow their departures to push back from gates immediately when ready, only to be delayed in long departure queues, some carriers delay pushback to save fuel. The practice is common where an air carrier's departures comprise most of the traffic at an airport – as at a hub or during a cargo push. For example, Delta Airlines manages departures at Atlanta, United Airlines at Newark, and UPS at Louisville.

OPERATIONS CONTROL

Operations control is a second function in an airline's operational organization that benefits from traffic flight and flow data. These personnel are typically housed in an air carrier's operations control center and major hubs. They are responsible for making decisions about delaying, cancelling and diverting flights as well as for allocation of aircraft, crews and gates. These decisions are made with regard to schedule integrity and performance, operating costs and passenger experience.

Operations control maintains a picture of the airborne and surface situations, especially at its major hubs. They too have a variety of information systems at their disposal. Some are the same as those used by ramp controllers, and others merely share databases. For larger air carriers, operations control is closely associated with separate groups that manage the fleet, pilots and cabin crews. Operations control also interacts with FAA traffic flow management and monitors its outlook, plans and traffic management initiatives.

Operations control uses surveillance data partly to gain better insight into the status and future of individual flights. Two examples of the benefits of this insight arise from a better awareness of delayed arrivals. Multiple interviewees noted that such awareness implies awareness of the unplanned availability of a gate. Another example concerned decisions about whether to hold departures for connecting passengers. On the one hand, surveillance data may reveal that an inbound arrival is minutes from its gate. On the other, it may reveal that an arrival is several aircraft back in a de-icing queue at its origin.

Surveillance data provided by the FAA also informs decisions about departures. Several interviewees noted that surveillance data enables automated alerts about long taxi-out times. These alerts help operations control maintain awareness of crew duty-time limitations and compliance with the Department of Transportation Tarmac Delay Rule. Another noted the value of knowing departure times managed by the TBFM departure scheduling function in avoiding unnecessarily early pushbacks from the gate.

While decisions made by an air carrier's operations control are ultimately about individual flights, these personnel also need to monitor and predict system performance and available capacity. Surveillance data helps these tasks as well. For example, simple measurement of aircraft movements over time informs expectations about how quickly flights will progress through de-icing and departure queues. Interviewees also reported interest in leveraging new traffic flow management (TFM) data via SWIM, motivated by the need to maintain awareness of available capacity and to engage with new collaborative mechanisms to allocate that capacity (e.g., Collaborative Trajectory Options Program). However, they report that modification of legacy internal systems is a slow process and that they anticipate more maturation of the new TFM data products before deciding how to best leverage them.

FLIGHT DISPATCH

Flight dispatch is another air carrier function that relies on FAA-provided information. Dispatchers plan for safe and efficient flights by coordinating with pilots on routes, procedures, alternate airports, fuel loading, and weight and balance. They are concerned with aircraft performance characteristics, aircraft and crew certification, runway capabilities, winds, adverse weather, airspace restrictions, advisories and traffic management initiatives. Dispatchers access more dynamic information from a variety of sources, including information systems and communications with pilots and operations control.

Dispatchers have been the beneficiaries of some improvements to FAA data sharing but not to the extent of ramp controllers and operations control. One reason is that dispatchers focus on the details of individual flights and are less involved with maintaining schedule integrity or managing traffic situations. While surface surveillance data is not helpful to dispatchers, en route surveillance data in the form of ASDI is valuable in their flight-following responsibilities. One airline has a feature of its software that detects and alerts dispatchers to deviations from the planned flight route so that a dispatcher may replan if warranted. However, only one of the interviewed dispatchers uses an automated tool for dynamic in-flight replanning.

Dispatchers also tend to rely on third-party providers for most of the aeronautical and weather information used in their planning. These providers collate information from various government and non-government sources into packages that are specific to individual flights or onto displays with integrated graphics. Our interviewees reported no benefits yet to dispatchers of new weather and NOTAM products available via SWIM. However, they expressed interest in eventually leveraging some of these products as they mature. They mentioned that investment in access to federal NOTAMs, ITWS products, surface and terminal area winds, and Digital Automatic Terminal Information Service might be attractive if these were easily parsed—in particular, if information began to appear in taggable data fields rather than in free text.

SAA was one type of dynamic aeronautical information of great interest. Dispatchers become familiar with common airspace restrictions on routes they plan regularly and use ad hoc means of monitoring their status. The FAA has worked to improve the collection and dissemination of SAA status information. Our interviewees report that the content of SAA data over SWIM is too often incomplete or not recent enough to be useful.

One noteworthy information product of value to dispatchers is RVR data. RVR describes visibility on the runway and governs the eligibility of flights to conduct various instrument approach procedures. Dispatchers monitor RVR trends at their flights' destinations to inform their pilots about what approaches to plan for and also to make decisions about whether to divert. As noted above, the Air Traffic Control System Command Center has been sharing RVR data on its website for some time, but RVR data is now available to other information systems via SWIM.

GATE AND GROUND RESOURCE MANAGEMENT

Real-time surveillance data is used to alert gate agents and ground crews when an arriving flight needs to be serviced. Prior to the availability of this data, personnel could be uncertain about when an aircraft would arrive. With real-time surveillance data, gate and ground personnel can monitor inbound aircraft more precisely and be ready at exactly the right time. At least one air carrier even has automated alerts to advise ground crews that they need to prepare to receive the flight.

PLANNING AND ANALYSIS

To this point, we discussed the use of FAA-provided data by air carrier operations personnel. The data also are used by their planning and analysis staff. These staff members are responsible for understanding the use and performance of resources used in their operations. The airline industry is historically data-conscious and a leader in various fields of operations planning. It is not surprising that these groups would collect and use newly provided data from the FAA to improve their efficiency.

However, our interviews did not reveal specific instances of planning influenced by FAA-provided data. Rather, a few likely scenarios emerged. One is that the ability to play back operations facilitates collaboration between planning and operations. An example one interviewee shared involved the routine early arrival of a flight and the lack of a gate.

Another possibility is that if ramp towers can more precisely choreograph aircraft movement, then planners can be less conservative in separating arrivals and departures. An airline whose bank schedule currently flushes departures from their gates 20 minutes before arrivals begin to enter the alley may be willing to reduce this to 15 minutes if the overlap can be efficiently managed.

Finally, plans and schedules may reflect better performance enabled by operational use of better data. If alerting functions get ground crews to aircraft more quickly, perhaps scheduled turn times could decrease. If taxi-out times improve because ramp tower controllers avoid congestion, maybe scheduled block times could decrease.

BENEFITS TO AIRPORT OPERATORS

The availability of surveillance data on the surface and in the terminal area helps some airport operators as well. The following sections describe benefits to airport operators by user role, with a summary presented in Table 4.

DEPARTURE QUEUE MANAGEMENT

At JFK airport, the Port Authority of New York and New Jersey manages departure queues on behalf of all air carriers. This was originally established as a measure to deal with departures during a runway improvement project in 2010. Subsequently, at the prompting of the air carriers, this coordination between the Port Authority's operations control center and the airport ramp towers continued for more than five years. The concept is to limit the number of aircraft simultaneously moving toward the same runway by issuing specific times to push back from gates. In order to facilitate the process, a third party provides a decision support system to the airport, which relies on FAA surface traffic data to monitor the departure queues, as well as recent runway service rates.

SURFACE TRAFFIC MANAGEMENT

Massport, the owner of Boston's Logan Airport (BOS), uses FAA surveillance data for various surface traffic management functions. One is tactical management of its ground vehicles, much like ramp towers manage aircraft. Massport equipped a large number of its ground vehicles at BOS with Automatic

Table 4 – Summary of the Benefits to Airport Operators

User Role	Operational / Performance Impact	Data Sets Used
Departure queue management	Metering aircraft to the departure runway • A few busy airports manage the departure queue for their resident airlines. By using real-time data on the length of the physical departure queues, these airports are able to meter aircraft pushing back from the gate and entering the taxiway.	• STTDS surface movement data
Surface traffic management	Managing ground vehicle operations • Surface surveillance data enhances the safety of ground vehicles operating on the airfield. This is particularly true during snow removal or other irregular operations.	• STTDS surface movement data

Dependent Surveillance System-Broadcast and integrated this surveillance information with its ASDE-X feed for a full picture of surface movement. This proves especially helpful during snow removal, irregular operations and emergencies.

Massport also uses FAA surveillance data in its noise monitoring program. This allows them to link specific noise profiles with the flights that generated them, and has proven helpful in responding to community inquiries about specific flights.

BENEFITS TO FLYING PUBLIC

Perhaps the most dynamic use of real-time surveillance data outside the FAA is for the purpose of providing flight tracking services to the flying public and aviation businesses. Through web browsers and mobile apps, subscribers to such services can access current information about flight and airport status and delays. In addition to real-time tracking services, data analyses and trending also are available.

The FAA did not attempt to assess these benefits to the traveling public, but we note them here for completeness.

SUMMARY

Airlines and airports report using FAA data to improve their operations, and they support their claims with concrete examples. The most extensive use of data was in support of improved awareness of the operating conditions and flight status, especially on the airport surface and in situations when aircraft transition from the control of one entity to another. Typically, improved awareness enabled more proactive engagement with flight replanning, including the ability to anticipate dynamically evolving conditions and events affecting individual flights as well as overall flows of traffic. Of course, all of this means improved resource management by the data consumers, especially when supported by automated decision support tools and ex post analytical capability.

One of the threads that runs through this discussion is that the data consumed by end-users was useful because it was in a format that could be combined with other types of information. For example, ASDE-X surface surveillance data can be displayed on a screen, but it also can be combined with actual and scheduled time information to yield useful decision-support applications. On the other hand, users said that aeronautical information about airspace restrictions will be more useful once it is fully digitized and can then be combined with planned flight trajectories in various decision support tools.

While the data sets they most relied on were the STDDS and TFMS feeds, users reported being interested in using additional data products once they become more mature. Our research confirms that obtaining the live subscriptions is only the first step that needs to be followed by developing parsers, displays and automation before the data becomes truly useful. External users now consume just a subset of the data made available over time. Some of the data elements are new and require additional time for users to understand, which is necessary for determining their practical use potential. Also, the cost of developing tools that transform this data into valuable information remains the key impediment to more extensive use.

Because the FAA provides the data it shares free of charge, there has always been a question about its actual value. Of course, end-users expend resources to get this information, either by investing their own time and money to connect to the data and parse it or by paying a third-party vendor for the service. This is only a partial picture of the value proposition. In any case, the amount spent on these transactions was not available to inform our study.

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